Army Research Laboratory

A Human Factors Evaluation of Exoskeleton Boot Interface Sole Thickness

by Angela C. Boynton and Harrison P. Crowell III

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Human Research and Engineering Directorate, ARL

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14. ABSTRACT
The purpose of this study was to identify potential human factors issues related to the sole thickness of an exoskeleton boot interface. Twelve Soldiers were evaluated in three footwear conditions (no additional sole, 1-inch sole, and 2-inch sole). Lower extremity biomechanics were assessed for walking, running, squatting, and kneeling with the use of a force plate and motion capture system. Mobility performance was assessed with five obstacles on a mobility-portability course. Participants also provided subjective feedback on each footwear condition’s comfort, stability, and difficulty during the biomechanics and mobility assessments. Results indicate that an exoskeleton could incorporate a boot interface as thick as 2 inches without substantially impacting the human factors issues evaluated in this study.

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Executive Summary

Development of a wearable, anthropomorphic, powered exoskeletal device intended to increase the speed, strength, and endurance of Soldiers in combat situations is currently being funded by the Defense Advanced Research Projects Agency (DARPA) through the Exoskeletons for Human Performance Augmentation (EHPA) program. The exoskeleton boot interface, an integral component of the system, is expected to incorporate a 1- to 2-inch-thick sole for the containment of force sensors, thus creating a substantial offset of the Soldier's foot from the ground. Very little published data exist regarding human factors issues related to footwear sole thickness; therefore, the objective of this investigation was to identify any biomechanical, mobility performance, and subjective assessment issues related to the additional sole thickness of an exoskeleton boot interface. In this investigation, the examined biomechanical variables included three-dimensional (3-D) angles, moments, and powers at the right hip, knee, and ankle joints during walking, running, squatting, and right and left kneeling. The measured mobility performance variables were stride time, stride length, velocity, and percent stance during walking and running; cycle time during squatting and right and left kneeling; and time to negotiate obstacles. The subjective assessments included ratings of comfort, stability, and difficulty during walking, running, squatting, kneeling, and negotiating obstacles. There were three footwear conditions: baseline (no additional thickness added to the boot sole), 1 inch of thickness added to the boot sole, and 2 inches of thickness added to the boot sole. The results of this investigation will provide critical guidance to the DARPA EHPA program for the development of an exoskeleton boot interface that is safe, comfortable, and functional and may also result in substantial savings of time and money for the EHPA program.

Twelve male Soldiers stationed at Aberdeen Proving Ground (APG), Maryland, participated in this study. Rubber overboots with detachable wooden soles were used to create the three sole conditions. For each of the three footwear conditions, 3-D positions of reflective markers placed on the participants' boots and at several anatomical locations were tracked by six high-resolution video cameras as participants walked, ran, squatted, kneeled on their right knees, and kneeled on their left knees on a force plate surrounded by a raised walkway. Sixty-four biomechanical variables for walking and running and 61 biomechanical variables for squatting and kneeling were calculated from the ground reaction force and 3-D marker data. Individual completion times under the three sole conditions were collected for five obstacles (log balance, elevated up and down, tires, house, and zig-zag) on the U.S. Army Research Laboratory (ARL) mobility-portability course at APG. Subjective assessments of comfort, stability, and difficulty during walking, running, squatting, right and left kneeling and negotiating the five obstacles during the three sole conditions were obtained via a questionnaire with a six-point rating scale.

All participants were first briefed about the objectives of this investigation and procedures to be followed and were then asked to sign a statement of informed consent and to complete a medical

status form. After they signed the volunteer agreement, height, weight, and shoe size were measured and recorded for each participant. Before data collection for each sole condition, participants were trained to walk, run, squat, and kneel on the force plate and to negotiate each of the five obstacles correctly and were then permitted to practice until they were able to perform each movement comfortably.

With the Statistical Package for the Social Sciences (SPSS) 12.0 for Windows[1] (SPSS, Inc., Chicago, IL), the data were analyzed by multivariate analyses of variance. For those main and interactive effects found to be statistically significant (Wilks' $\lambda \leq 0.05$), a univariate analysis of variance was performed on each dependent variable with a significance level of 0.05. Dependent variables found to be significantly affected were further analyzed by a Sidak *post hoc* test for multiple comparisons to identify differences between levels of the main or interactive effect in question.

Twelve of the 61 squatting and kneeling biomechanical variables were found to be significantly affected by footwear condition, but this had no impact on the ability of the participants to correctly perform those movements. Responses to the comfort, stability, and difficulty questionnaire were also found to be significantly affected by footwear condition; however, the actual differences in mean ratings of comfort, stability, and difficulty for the baseline and 2-inch conditions are relatively small. Based on the results of this investigation, it appears that the exoskeleton boot interface could incorporate a sole as thick as 2 inches without substantial impact on any of the human factors issues investigated.

[1]Windows is a trademark of Microsoft.

1. Introduction

In 2000, the Defense Advanced Research Projects Agency (DARPA) issued a Broad Agency Announcement (BAA) soliciting proposals on Exoskeletons for Human Performance Augmentation (EHPA). In this BAA, DARPA outlined requirements for the development of wearable, anthropomorphic, powered exoskeletal devices to increase the speed, strength, and endurance of Soldiers in combat situations. Supplemental material to the BAA states that “the developed system should be ergonomic and must consider a variety of human factors,” and “to the greatest extent possible, human agility must be maintained and even enhanced.” The EHPA program is currently in the component development stage.

The exoskeleton boot interface is an integral part of the exoskeleton system. The boot interface will serve as one of two or three connection points between the Soldier and the exoskeleton, as well as being the only interface between the exoskeleton system and the ground. It has also been proposed that force sensors be incorporated into the exoskeleton boot interface so that it will also serve as part of the exoskeleton’s control system. Several concepts for the exoskeleton boot interface’s design have been proposed. In all cases, the boot interface incorporates approximately a 1- to 2-inch thick sole that will attach to the bottom of the boot, thus substantially offsetting the Soldier’s foot from the ground.

Very little published research exists regarding human factors issues related to the sole thickness of footwear. A few studies have been conducted concerning the effects of shoe sole hardness and thickness on foot position awareness, stability (Robbins, Waked, Gouw, & McClaran, 1994; Robbins, Waked, Allard, McClaran, & Krouglicof, 1997) and joint position sense (Sekizawa, Sandrey, Ingersoll, & Cordova, 2001). In both studies conducted by Robbins et al., foot position awareness and stability were found to be related, and shoes with thin, hard soles were found to provide better stability than those with soft, thick soles. Similarly, Sekizawa et al. found that joint position sense is affected by shoe sole thickness but only in dorsiflexion.

Our investigation sought to identify, through biomechanical evaluation, human performance evaluation, and subjective assessment, potential human factors issues related to the thickness of the boot interface’s sole. Identification of such issues early in the project will provide critical guidance in the development process and may result in substantial savings of time and money for the EHPA program.

2. Objectives

The overall objective of this investigation was to identify potential human factors issues related to the additional sole thickness of an exoskeleton boot interface. This was accomplished through analyses of biomechanical data, subjective assessments of comfort, stability, and difficulty, and observations of ability to negotiate obstacles in three footwear conditions: baseline (no additional sole thickness), 1-inch sole, and 2-inch sole.

The results of this investigation allowed us to

a. determine the effects of sole thickness on three-dimensional (3-D) lower limb joint angles, moments, and powers during walking, running, squatting, and kneeling;

b. determine the effects of sole thickness on stride length, stride time, velocity, and percent stance during walking and running;

c. determine the effects of sole thickness on cycle time for squatting and kneeling;

d. determine the effects of sole thickness on perceptions of comfort, stability, and difficulty during walking, running, squatting, kneeling, and negotiating obstacles;

e. determine the effects of sole thickness on obstacle completion times; and

f. provide guidance to the DARPA EHPA program for the development of an exoskeleton boot interface that is safe, comfortable, and functional.

3. Methodology

3.1 Participants

Twelve male Soldiers, stationed at Aberdeen Proving Ground (APG), Maryland, were recruited for participation in this investigation. Only male participants were used in this investigation, based on the fact that the exoskeletal system is being developed initially for combat Soldiers only. A summary of the participants' physical characteristics is presented in table 1. All participants were briefed about the objectives of this investigation, procedures to be followed, and risks associated with their participation. Before participating in this investigation, participants read and signed a statement of informed consent[2]. To eliminate the possibility of any illness or injury that could increase the risk to the participant or bias the data, participants were also asked to complete a medical status form.

[2]The investigators have adhered to the policies for protection of human subjects as prescribed in AR 70-25.

Table 1. Participants' physical characteristics (N = 12).

	Mean ± SD	Range
Age (yr)	21 ± 3	18 to 30
Height without shoes (cm)	172.5 ± 8.6	162.5 to 190.5
Body mass (kg)	76.0 ± 9.1	61.2 to 93.0
Shoe size (U.S. men's)	10 ± 1	7 to 11.5

3.2 Apparatus

3.2.1 Clothing

All participants wore their own physical training (PT) shorts and t-shirt or battle dress uniform (BDU) and standard issue combat boots throughout this investigation. Rubber overboots and plywood soles 1 inch and 2 inches thick were used to produce the experimental conditions. In the footwear conditions incorporating additional sole thickness, the rubber overboots had loop Velcro[3] placed on their bottoms to allow for secure attachment of the 1- and 2-inch soles. Each 1- and 2-inch sole was constructed from an appropriate thickness of plywood that had been shaped to the bottom of the rubber overboot, cut into two segments at a point coinciding with the metatarsophalangeal (MP) joint, topped with hook Velcro and covered with tread identical to that of the rubber overboots. This construction resulted in soles that were easy to attach and remove, lightweight, flexible and provided adequate traction. Several different sized pairs of 1- and 2-inch soles were constructed in order to accommodate various foot sizes. Also, in order to eliminate differences in footwear condition weight, lead insoles were inserted into the rubber overboots for the baseline sole condition, and the wooden soles for the 2-inch sole condition were partially hollowed so that both footwear conditions weighed the same as the 1-inch sole condition. Photographs of the overboot and sole setup are shown in figure 1. The U.S. Army Developmental Test Command issued a safety release for the overboots and soles, and its recommendations were followed throughout this study. Participants were also required to wear a personal armored system for ground troops (PASGT) helmet throughout training and obstacle negotiation on the mobility-portability course.

3.2.2 Force Plate (Advanced Mechanical Technology, Inc. [AMTI], Newton, MA)

A 1.22-m (4-ft) square AMTI force plate was used in this investigation to collect ground reaction force data for the right foot as subjects walked, ran, squatted, and kneeled on their right and left knees (figure 2). The force plate was surrounded by several solid platforms to create a level walkway along which the participants could walk and run. With strain gauge sensors, the force plate measures vertical and horizontal ground reaction forces (GRFs) (to approximately 17,800 N and 8,900 N, respectively), as well as torques about the vertical axis, at a maximum sampling rate of 1,000 Hz. The three GRF channels (Fx, Fy, Fz) have resolutions of 0.714, 0.722, and 3.052 Newtons, and the torque channels (Mx, My, Mz) have resolutions of 0.718, 0.714, and 0.315 Newton-meter. In this investigation, the force plate data were sampled at a rate of 120 Hz.

[3]Velcro is a registered trademark of Velcro USA, Inc.

Figure 1. Overboot and sole setup.

3.2.3 Motion Analysis System (Motion Analysis Corporation, Santa Rosa, CA)

The Motion Analysis System, which consists of six high-resolution video cameras and the EVaRT 4.0 Motion Capture software package, is capable of collecting and tracking the 3-D positions of reflective markers in real time. The EvaRT software can additionally collect data from analog devices (force plate, in this case) and synchronize them with the marker position data. In this investigation, the six cameras were arranged around a force plate and walkway, and reflective markers were placed on the participants' boots as well as at several anatomical positions (figure 3). Marker position data were collected at a rate of 60 Hz, with an accuracy of approximately 1.5 ±0.5 mm. The synchronized marker position and force plate were exported to a .c3d file for analysis via Visual3D Movement Analysis software (C-Motion, Inc., Rockville, Maryland).

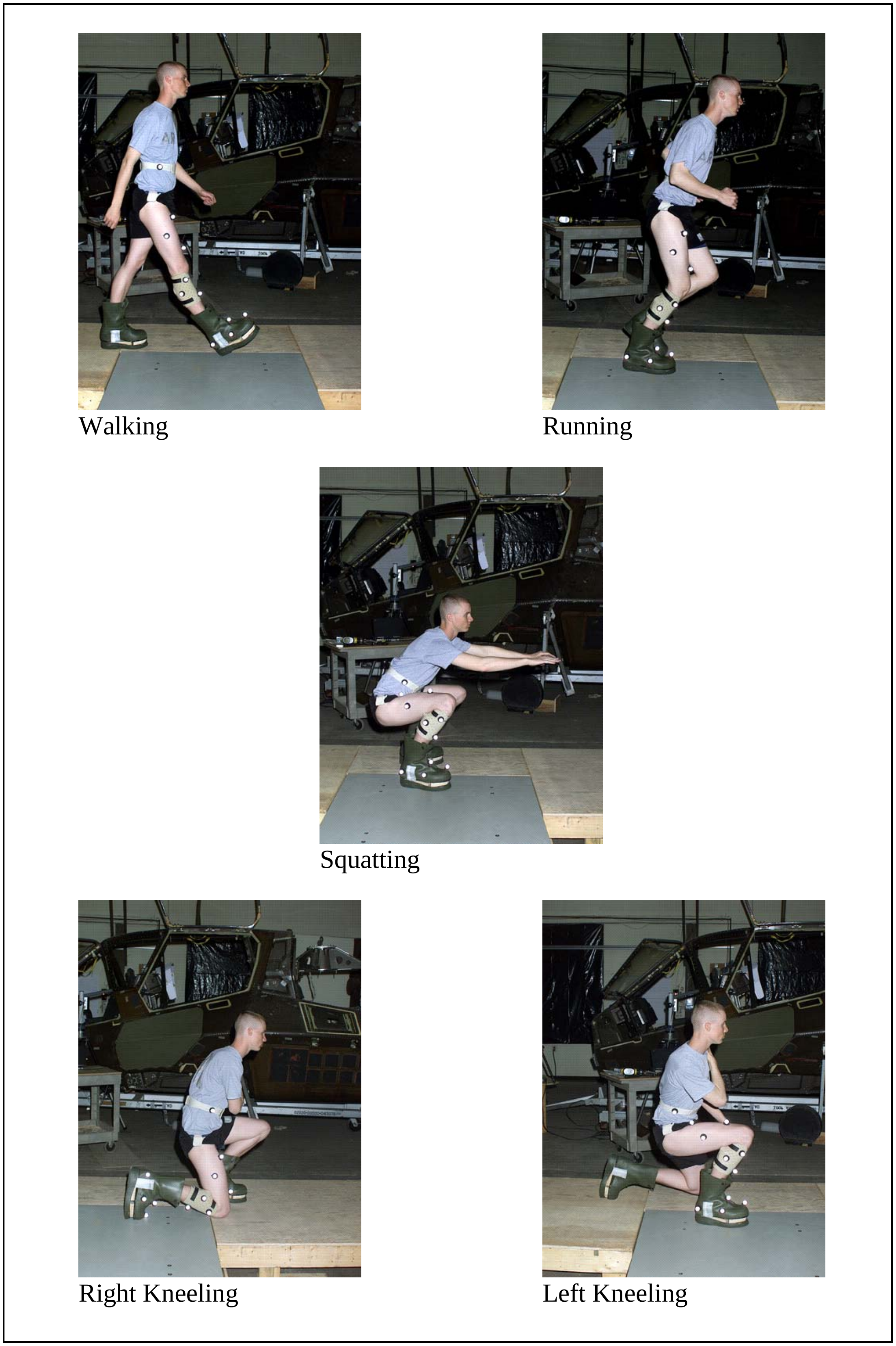

Figure 2. Walking, running, squatting, and kneeling on the walkway and force plate.

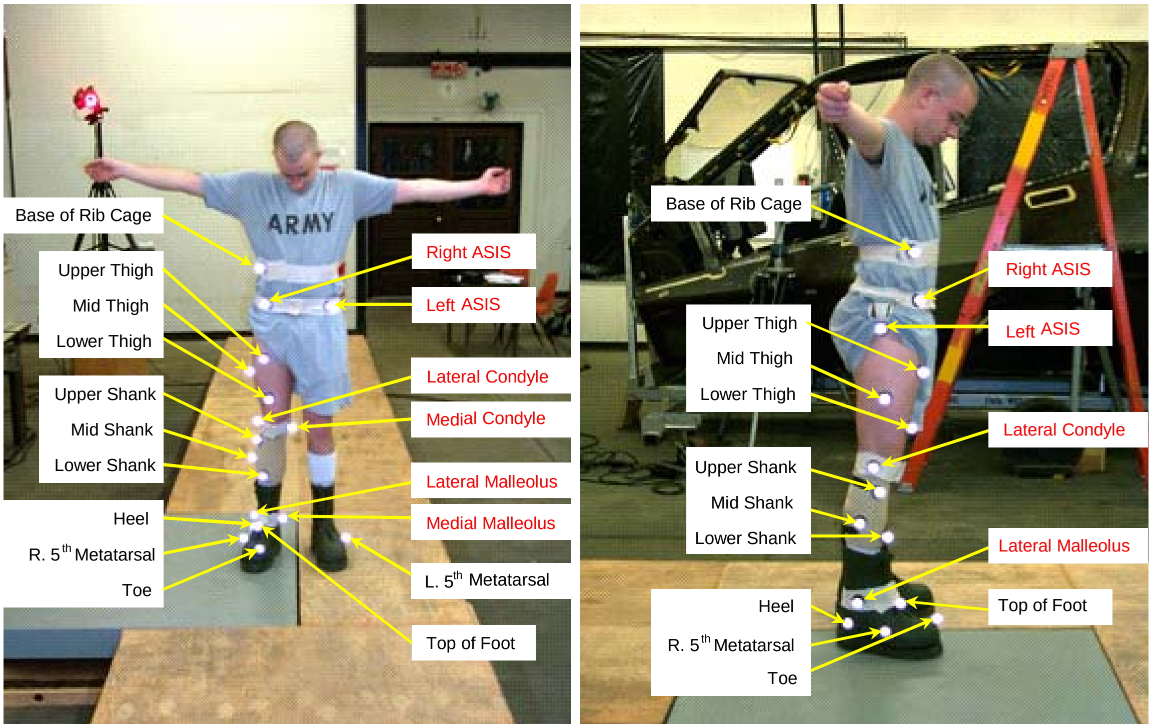

Figure 3. Reflective marker placement (red used for the neutral trial only, black used for neutral and motion trials).

3.2.4 Visual3D Movement Analysis Software (C-Motion, Inc., Rockville, MD)

The Visual3D software package uses a flexible 6 degree-of-freedom model to perform kinematic and kinetic (inverse dynamic) analyses on synchronized motion capture and analog data. Three-dimensional lower limb joint angles were calculated during walking, running, squatting, and kneeling; stride length, stride time, velocity, and percent stance during walking and running; and cycle time during squatting and kneeling with the use of the marker position data. Three-dimensional lower limb joint torques and powers were also calculated during walking, running, squatting, and kneeling with the use of the synchronized marker position and force plate data. Diagrams detailing the planes of motion, axes of rotation, and terminology used to describe joint motion are presented in appendix A.

3.2.5 U.S. Army Research Laboratory (ARL) Mobility-Portability Course

The ARL mobility-portability course at APG is approximately 500 m long and consists of 20 pairs of identical obstacles, thus allowing two subjects to negotiate the course simultaneously without interfering with one another. Negotiation of the obstacles requires running, jumping, climbing, and crawling. It has been shown that the movements performed by Soldiers negotiating obstacles on this course allow for identification of human factors issues associated with individual equipment (Hanlon et al., 1984; Hanlon, Hickey, & Ortega, 1990). In this part of the investigation, objective data (time to complete obstacle), observations, and participant feedback were collected to determine if differences resulting from the various footwear conditions exist in the negotiation of five selected obstacles. Obstacle completion times were

measured with mechanical stopwatches. The five obstacles used in this investigation were the log balance, elevated up and down, tires, house, and zig-zag (figure 4).


Log Balance


Elevated Up and Down


Tires


House


Zig-zag

Figure 4. Obstacles on ARL's mobility-portability course.

3.3 Procedures

3.3.1 Volunteer Consent

The volunteers were first briefed about the objectives of this investigation, procedures to be followed, and the potential risks associated with their participation. Proper procedures for walking, running, squatting, and kneeling on the right and left knees were demonstrated. A video of a Soldier negotiating each of the five obstacles was also shown to the volunteers. They were given an opportunity to examine the overboots and soles. Any questions they had regarding their participation were then answered. The volunteer agreement affidavit was read aloud to them by the investigator as they followed. They were then asked individually whether they chose to participate in this investigation. After consenting to participate, each volunteer, along with the investigator, initialed the bottom of each page and answered and signed the last page of the volunteer agreement affidavit. As part of the affidavit, permission to obtain the participant's Armed Services Vocational Aptitude Battery (ASVAB) scores was also requested. After completing the affidavits, volunteers completed the medical status form and were assigned participant numbers to preserve anonymity and for use in identification throughout data collection.

3.3.2 Training

3.3.2.1 Biomechanics

Participants were individually trained to walk and run across the force plate, as well as squat and kneel on the force plate, before data were collected for each of the three footwear conditions. In order to eliminate force plate targeting during the walking and running trials, starting positions that allowed the subject's right foot to land squarely near center of the force plate without modification of gait were first identified. They were then given an opportunity to practice walking and running across the force plate. Participants were considered trained for walking and running when they were able to place their feet in the proper location on the force plate for three consecutive passes. After participants had been trained to walk and run across the force plate, they were also given an opportunity to practice squatting and kneeling on the force plate. Participants were considered trained for squatting and kneeling when they felt capable of performing the movements in a consistent manner. Following training, participants were provided with a 15-minute break.

3.3.2.2 Obstacle Negotiation

Participants were trained to negotiate five obstacles on the mobility-portability course. They were first instructed in the proper method for negotiating each obstacle and were then given an opportunity to familiarize themselves with negotiating each obstacle in the three footwear conditions before data collection. Participants were considered trained when they felt confident in their ability to negotiate each obstacle properly. Following training, participants were provided with a 15-minute break.

3.3.3 Data Collection

3.3.3.1 Biomechanics

For each of the three footwear conditions, motion and force plate data were collected for the right leg of each participant as he performed five movements (walking, running, squatting, kneeling on left knee, kneeling on right knee). Footwear conditions were presented to each participant according to a Latin square counterbalancing scheme. Before the motion trials for each footwear condition, a neutral (standing) trial was collected to be used later in building the Visual3D model. During the walking and running trials, the participant proceeded along the walkway at a self-selected speed, striking the center of the force plate with his right foot as he passed over it. During the squatting, kneeling on the left knee, and kneeling on the right knee trials, the participant began and ended in a standing position with his right foot flat on the force plate and left foot flat on the walkway. When kneeling on the left knee, the participant moved down into a kneeling position while keeping his right foot on the force plate and placing his left knee on the walkway. When kneeling on the right knee, the participant moved down into a kneeling position while keeping his left foot on the walkway, right foot on the force plate and placing his right knee on the walkway. Following the data collection period for each footwear condition, the participant was asked to complete part A of the comfort, stability, and difficulty questionnaire (see appendix B). Each data collection period lasted for approximately 15 minutes and was followed by a 15-minute break.

3.3.3.2 Obstacle Negotiation

The ability of each participant to negotiate five obstacles on the mobility-portability course was assessed for each of the three footwear conditions. As with the biomechanical data collection, footwear conditions were presented to the participants according to the counterbalancing scheme. Participants negotiated each of the five obstacles, while observers recorded the time required for the participants to negotiate each obstacle and any footwear-related problems encountered. After negotiating each of the five obstacles, participants were asked to complete part B of the comfort, stability, and difficulty questionnaire.

3.4 Experimental Design

3.4.1 Independent Variables

The independent variables in this investigation were footwear condition, trial during which the footwear condition was presented, and movement performed. Footwear condition consisted of three levels: no additional sole thickness, 1-inch sole, and 2-inch sole. Trials consisted of three levels: first, second, and third. Movement consisted of five levels for the biomechanical analysis (walking, running, squatting, kneeling on the right knee, and kneeling on the left knee) and five levels for the obstacle negotiation (log balance, elevated up and down, tires, house, and zig-zag).

3.4.2 Dependent Variables

The following dependent variables were calculated from the biomechanical data for each of the three footwear conditions:

a. peak 3-D joint angles at the ankle, knee, and hip (degrees);

b. peak 3-D joint moments at the ankle, knee, and hip (Newton-meters/kilogram);

c. peak 3-D joint powers at the ankle, knee, and hip (watts/kilogram);

d. peak ground reaction forces normalized to body weight (Newtons/body weight)[4];

e. stride length (meters), walking and running trials,

f. stride time (seconds), walking and running trials,

g. velocity (meters/second), walking and running trials,

h. percent stance, walking and running trials; and

i. cycle time (seconds), squatting and kneeling trials.

The dependent variable associated with obstacle negotiation was time. With respect to the questionnaire, the dependent variable was the participant's response to each question.

3.4.3 Statistical Analysis

All statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS) 12.0 for Windows[5] (SPSS, Inc., Chicago, IL). The biomechanical variables, obstacle completion times, and questionnaire responses were analyzed by multivariate analyses of variance (MANOVAs). A Wilks' λ value of 0.05 or less was considered statistically significant. For those main and interactive effects found to be statistically significant, a univariate analysis of variance (ANOVA) was performed on each dependent variable, and the results were considered statistically significant for p-values of 0.05 or less. Dependent variables found to be significantly affected were further analyzed via a Sidak *post hoc* test to identify differences between levels of the main or interactive effect in question. The significance level of the Sidak *post hoc* test was adjusted for multiple comparisons according to the formula $1-(1-\alpha)^{1/k}$, in which α is equal to overall significance level and k is the number of comparisons. Therefore, given an overall significance level of 0.05 and 3 comparisons, the calculated adjusted significance level was 0.017.

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[4]Body weight has units of Newtons; it is calculated when weight in kilograms is multiplied by acceleration attributable to gravity (9.81 meters/second^2)

[5]Windows is a trademark of Microsoft.

4. Results

4.1 Biomechanical Variables

Summaries of the biomechanical data for walking, running, squatting, and right and left kneeling under each of the three footwear conditions are given in appendix C, tables C-1 through C-5, respectively. Stride time, stride length, velocity, percent stance and cycle time are reported as mean values. Ground reaction forces, and 3-D joint angles, moments, and powers are reported as means of the peak values. Plots of mean ground reaction forces, and 3-D joint angles, moments and powers over one stride or cycle of each movement are presented in appendix D.

Based on the number of variables measured, data for the five movements were divided into two groups: walk/run and squat/kneel. A MANOVA with main effects for movement, footwear condition, trial and participant, and interaction effects for movement*footwear condition, movement*trial and footwear condition*trial, was performed on each group. For the walk/run group, a statistically significant effect was found only for movement ($p = 0.016$) and participant ($p = 0.000$). Since these effects were expected, no further analyses were conducted. However, for the squat/kneel group, in addition to movement ($p = 0.000$) and participant ($p = 0.000$), a statistically significant main effect was identified for footwear condition ($p = 0.028$). Each of the biomechanical variables for the squat/kneel group was independently analyzed for footwear condition effects by an ANOVA with Sidak *post hoc* test.

Of the 61 biomechanical variables analyzed for the squat/kneel group, 12 were identified as being significantly affected by footwear condition. Their mean values and *post hoc* analysis results are presented graphically in figure 5. Cycle time, peak ankle abduction, peak ankle external rotation, and peak ankle dorsiflexor moment all tend to increase with increasing sole thickness, but only the 2-inch condition mean was found to differ significantly from the baseline mean. Peak hip flexion, peak knee flexion, and peak knee extensor moment also tend to increase with increasing sole thickness, and both the 1- and 2-inch condition means were found to differ significantly from the baseline mean but not from each other. Peak ankle adduction and peak ankle internal rotation both tend to decrease with increasing sole thickness; however, only the baseline and 2-inch condition means were found to be significantly different from one another. No difference in condition means was identified for peak hip extension, peak ankle abductor moment, or peak ankle adductor moment.

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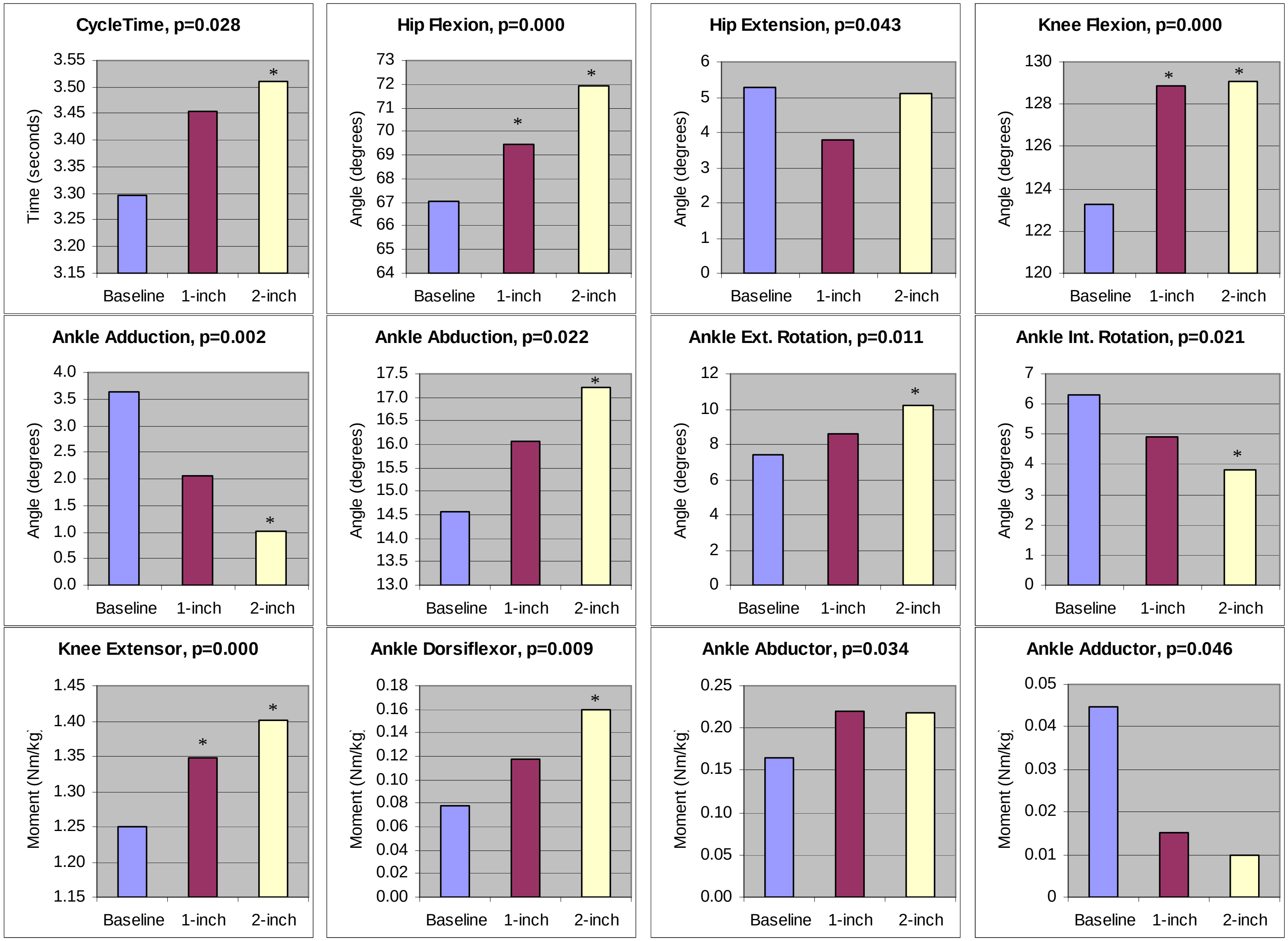


*based on *post hoc* analyses, indicated mean differs significantly from baseline mean

Figure 5. Mean values for squat/kneel group biomechanical variables significantly affected by footwear condition.

4.2 Obstacle Completion Times

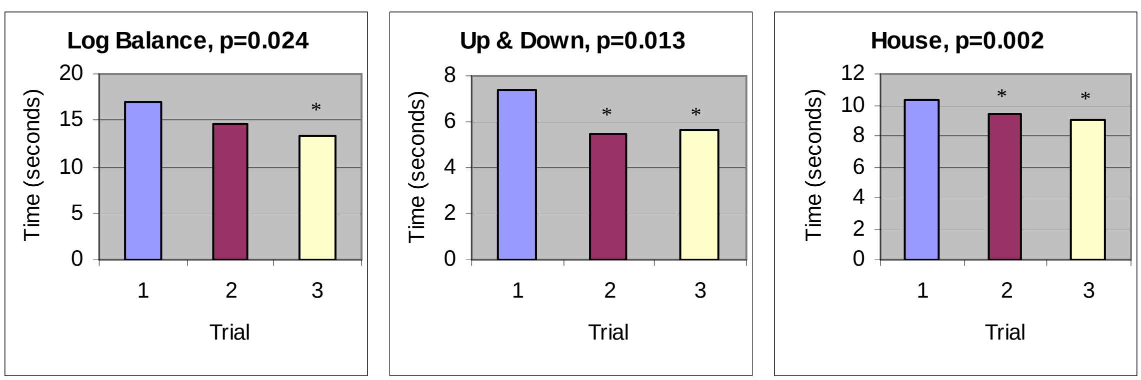
Mean obstacle completion times under each of the three footwear conditions are shown in table 2. Obstacle completion times were analyzed by a MANOVA with main effects for footwear condition, trial and participant, and interaction effect for footwear condition*trial. A statistically significant effect was identified for trial (p = 0.034) and participant (p = 0.000). Footwear condition was not found to significantly affect obstacle completion times. Further analysis of trial effects was performed on the individual obstacle completion times with an ANOVA with Sidak *post hoc* test.

Table 2. Obstacle completion times (seconds).

Obstacle	Footwear Condition		
	Baseline	**1-inch Sole**	**2-inch Sole**
Log Balance	12.7 (3.0)	15.4 (3.4)	16.0 (4.4)
Up and Down	5.4 (1.0)	6.0 (2.2)	6.4 (3.0)
Tires	7.8 (0.9)	8.3 (1.3)	8.7 (1.4)
House	9.3 (0.9)	9.5 (1.2)	9.9 (1.8)
Zig-zag	5.9 (0.7)	5.9 (0.7)	6.3 (0.9)

Note: values given as mean (SD), N=12

A statistically significant effect of trial was identified for the log balance (p = 0.024), up and down (p = 0.013) and house (p = 0.002). Their mean values and *post hoc* analysis results are presented graphically in figure 6. The time to complete each of the three obstacles tended to decrease with each run through the course. For the log balance, a significant difference in mean times was identified between the first and third runs only. For the up and down and house, the mean times of the second and third runs were found to differ significantly from that of the first run but not from one another.



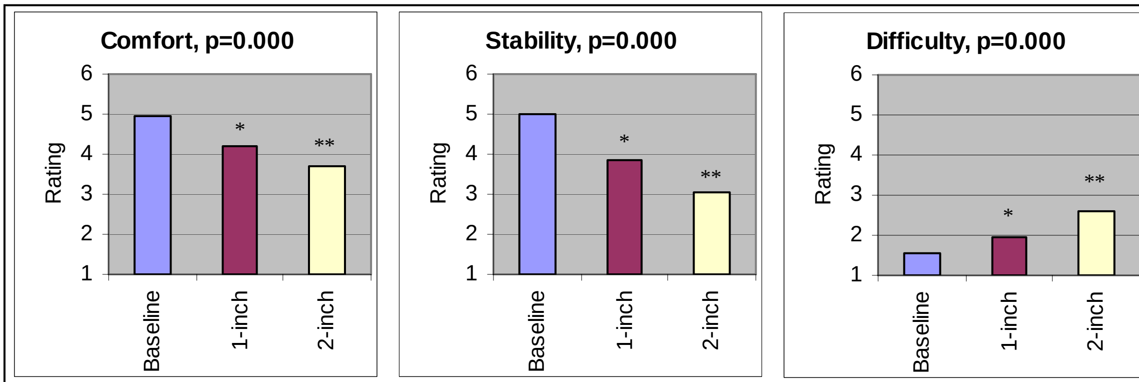
*based on *post hoc* analyses, indicated mean differs significantly from first run mean.

Figure 6. Mean values for obstacle times significantly affected by trial.

4.3 Comfort, Stability, and Difficulty Questionnaire Responses

In order to compute mean values and conduct statistical analysis of the questionnaire responses, each response level was assigned a numerical value: 1=very low, 2=low, 3=slightly low, 4=slightly high, 5=high, 6=very high. A MANOVA with main effects for activity, footwear condition, trial and participant, and interaction effects for activity*footwear condition, activity*trial and footwear condition*trial, was performed on the responses. Statistically significant main effects were identified for footwear condition (p = 0.000), trial (p = 0.024), activity (p = 0.000), and participant (p = 0.000). Further analysis of footwear condition and trial effects was performed on the questionnaire responses by ANOVAs with Sidak *post hoc* tests.

Mean values and *post hoc* analyses results for the effect of footwear condition on the comfort, stability and difficulty questionnaire responses are presented graphically in figure 7. Ratings of both comfort and stability tended to decrease, while ratings of difficulty tended to increase with increasing sole thickness. For all three, mean ratings for the 1- and 2-inch conditions were found to differ significantly from those for the baseline condition, as well as from one another. ANOVA results for the effect of trial were not significant.



*based on *post hoc* analyses, indicated mean differs significantly from baseline mean.
**based on *post hoc* analyses, indicated mean differs significantly from baseline and 1-inch means.

Figure 7. Mean values for questionnaire responses across footwear conditions.

5. Discussion

According to the BAA issued by DARPA for the EHPA program, the developed exoskeletal system must take into account ergonomics and other human factors considerations and must maintain or enhance human agility. Therefore, the purpose of this study was to identify potential human factors issues related to the additional sole thickness of an exoskeleton boot interface. This was accomplished through the evaluation of biomechanical variables for five movements, time to negotiate five obstacles, and subjective ratings of comfort, stability, and difficulty, during three different footwear conditions.

A statistically significant effect of footwear condition was identified only for the squatting/ kneeling biomechanical data and the questionnaire responses, and of the 61 biomechanical variables measured, only 12 were found to be significantly affected by footwear condition (see figure 5). The affected angular measures (hip flexion, knee flexion, ankle abduction and adduction, and ankle internal and external rotation) were still within the normal range of motion for their corresponding joint (Norkin & White, 1985). Additionally, ankle dorsiflexor, adductor and abductor moment values were within the same range as those normally seen during walking (Eng & Winter, 1995), while knee extensor moment values were within the same range as those normally seen during running (DeVita, Torry, Glover, & Speroni, 1996). The changes observed in maximum and minimum ankle angles in the frontal and transverse planes, along with increased hip and knee flexion and increased knee extensor and ankle dorsiflexor moments may indicate an adaptation in balancing strategy and stability control during squatting and kneeling because of the increasing sole thickness. The increased amount of time required to squat and kneel as sole thickness increased could possibly be attributed to the participant's decreased sense of stability, as indicated by the questionnaire responses.

As one might expect, with respect to the questionnaire, ratings of comfort and stability decreased, while ratings of difficulty increased with increasing sole thickness. The actual differences in baseline and 2-inch ratings, however, were quite small. Mean ratings of comfort and stability decreased from "high" to just above "slightly low," while mean ratings of difficulty increased from between "very low" and "low" to between "low" and "slightly low".

Interestingly, with respect to the obstacle completion times, trial was found to have a statistically significant effect on the log balance, up and down, and house times, but no effect of footwear condition was identified. Participants tended to complete the log balance, up and down, and house more quickly with each successive run, regardless of footwear condition. This is most likely indicative of a practice or learning effect and may have been eliminated if the number of training trials were increased or by training to achieve an asymptote in completion time, rather than allowing each participant to individually determine his own readiness. Running multiple trials for each footwear condition and then averaging the results may have been another viable solution to this problem.

From the values in table 2, it can be seen that completion times for each of the five obstacles showed an increasing trend with increased sole thickness. However, a statistically significant effect of footwear condition was not identified ($p = 0.39$), possibly because of the substantial effect of trial on obstacle completion time.

6. Conclusions

Of the human factors issues examined in this study, the effect of additional sole thickness on users' perceptions of comfort, stability, and difficulty is more important than its effect on the measured biomechanical variables. Mean ratings of comfort, stability, and difficulty for the 1- and 2-inch sole conditions are statistically different from mean ratings for the baseline condition, and although the differences are small, they point to areas that are important for user acceptance of a system. Therefore, it is important to design a comfortable and stable exoskeleton boot interface with an overall design goal to ensure that moving in the exoskeleton is as easy as moving in regular boots.

Despite the impact that footwear condition was observed to have on the values of a few of the squatting and kneeling biomechanical variables, all 12 participants were still able to perform the movements correctly. In addition, the biomechanical variables found to be significantly different from the baseline for squatting and kneeling are still within human range of motion limits and comparable to values seen for normal walking and running. Thus, their impact on the usability of an exoskeleton would probably be small. Additionally, walking and running are likely to be the two most frequent movements performed by a Soldier wearing an exoskeleton, and footwear condition failed to have a significant effect on the biomechanical variables for walking and running or the obstacle completion times.

Therefore, it appears that the exoskeleton boot interface, if designed to be comfortable and stable, could incorporate a sole as thick as 2 inches without substantial impact on any of the human factors issues investigated in this study.

7. References

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Appendix A. Three-Dimensional Biomechanics Terminology (from Hamill & Knutzen, 2003)

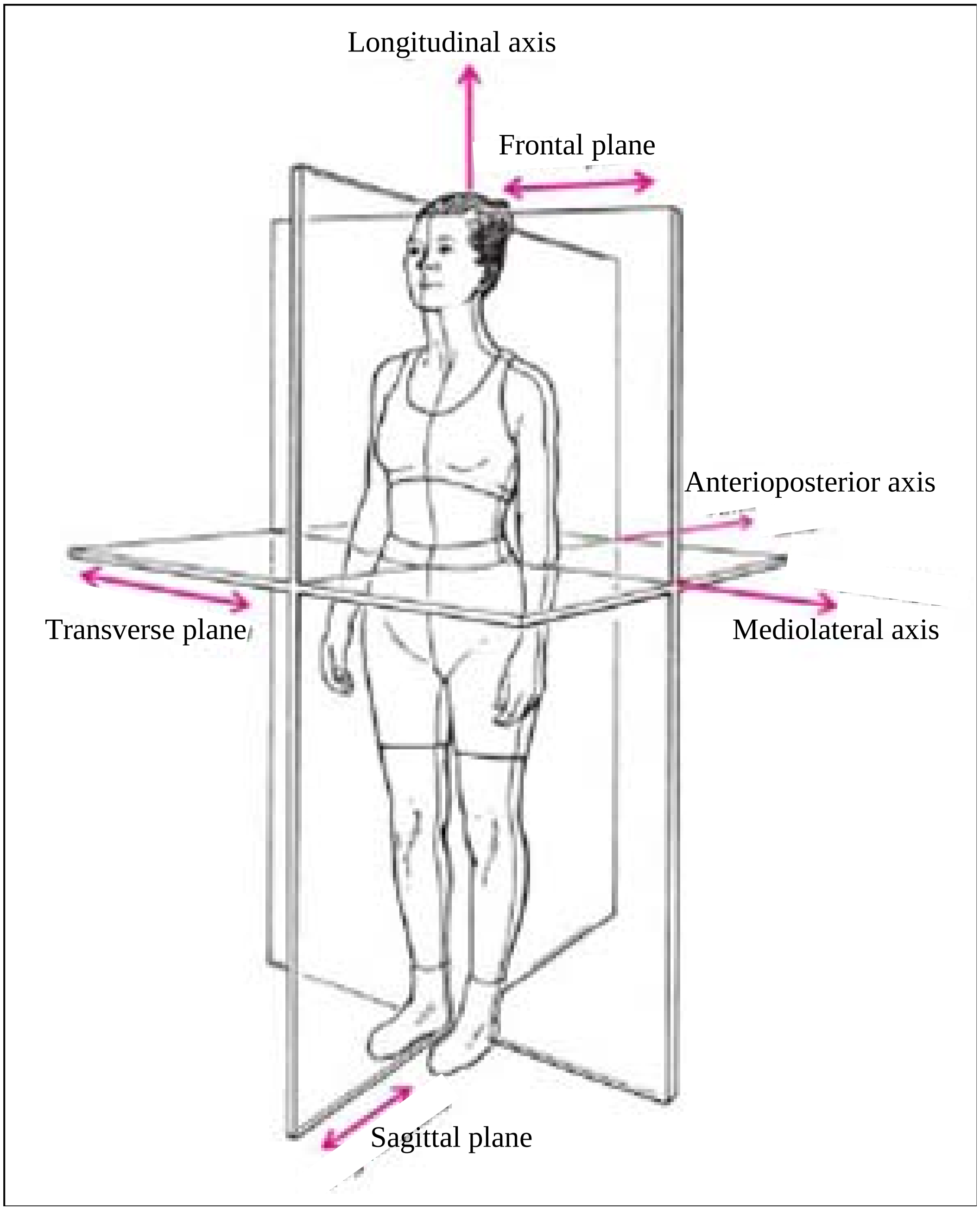

Figure A-1. Planes of motion and axes of rotation.

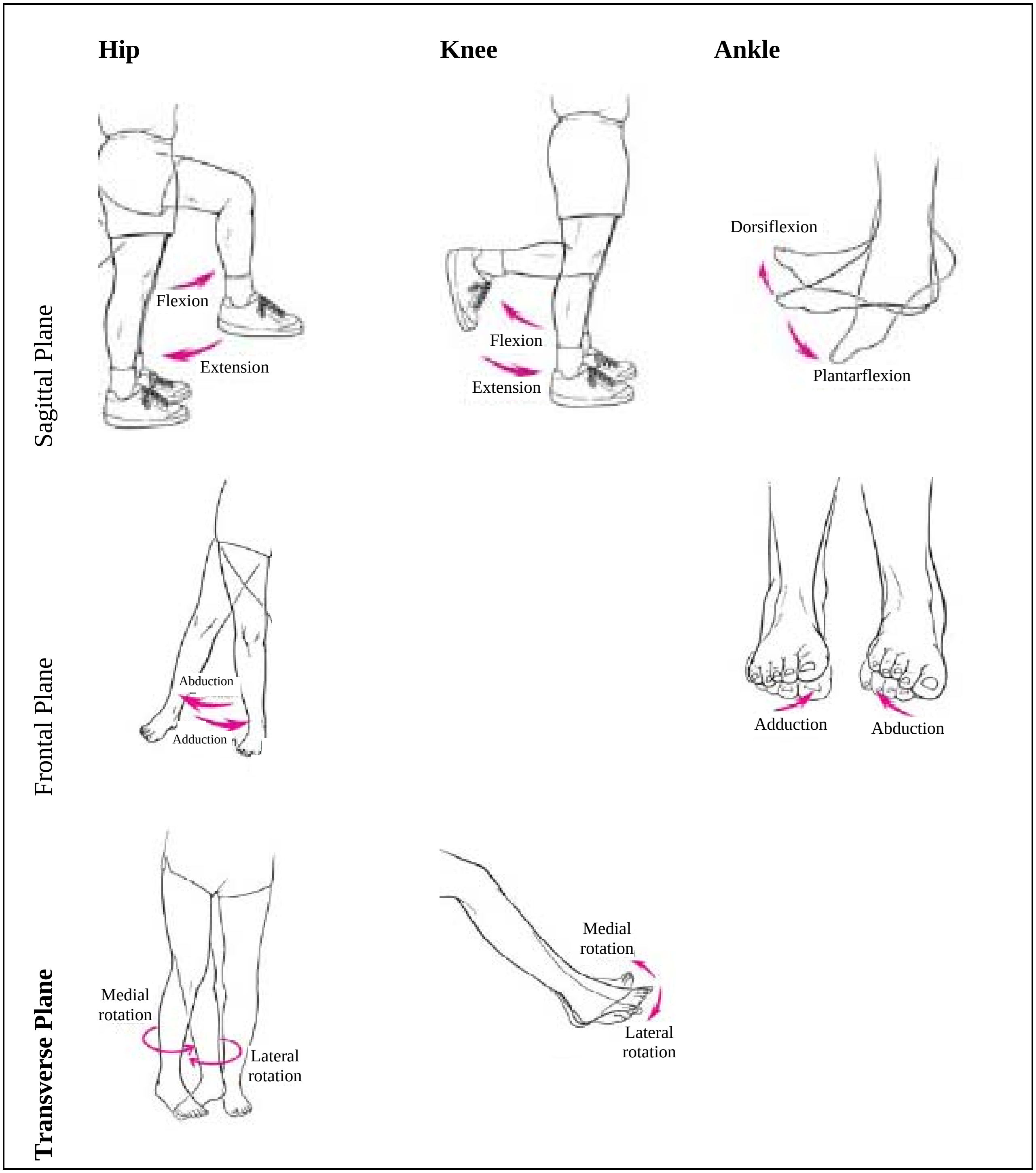

Figure A-2. Joint motion terminology.

Appendix B. Comfort, Stability, and Difficulty Questionnaire

Participant #: ________________________   Footwear Condition: ______________

Part A: For this footwear condition, rate each factor for each activity by placing an "X" in the box under the heading that best represents your feeling.

Activity	Factor	Very Low	Low	Slightly Low	Slightly High	High	Very High
Walking	Comfort						
	Stability						
	Difficulty						
Running	Comfort						
	Stability						
	Difficulty						
Squatting	Comfort						
	Stability						
	Difficulty						
Kneeling	Comfort						
	Stability						
	Difficulty						

Comments: ____

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Participant #: ________________________   Footwear Condition: ______________

Part B: For this footwear condition, rate each factor for each obstacle by placing an "X" in the box under the heading that best represents your feeling.

Obstacle	Factor	Very Low	Low	Slightly Low	Slightly High	High	Very High
Log Balance	Comfort						
	Stability						
	Difficulty						
Elevated Up & Down	Comfort						
	Stability						
	Difficulty						
Tires	Comfort						
	Stability						
	Difficulty						
House	Comfort						
	Stability						
	Difficulty						
Zig Zag	Comfort						
	Stability						
	Difficulty						

Comments: ____

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Appendix C. Biomechanical Variables Data Tables

Table C-1a. Temporal-spatial variables, joint angles and ground reaction forces for walking.

Variable				Sole Condition	
			Baseline	1-inch Sole	2-inch Sole
	Stride Length (m)		1.625 (0.124)	1.636 (0.114)	1.634 (0.111)
	Stride Time (s)		1.132 (0.050)	1.142 (0.078)	1.163 (0.070)
	Velocity (m/s)		1.439 (0.142)	1.439 (0.143)	1.413 (0.166)
	% Stance		60.2 (2.1)	62.9 (2.6)	61.4 (2.3)
Angle (degrees) – Sagittal Plane	Hip	Maximum	30.7 (4.1)	30.9 (3.8)	29.2 (3.5)
		Minimum	-21.6 (2.1)	-21.4 (3.3)	-21.7 (2.4)
	Knee	Maximum	73.3 (5.0)	71.8 (4.5)	68.3 (6.1)
		Minimum	-6.2 (3.6)	-3.7 (3.5)	-6.0 (5.8)
	Ankle	Maximum	10.6 (4.6)	12.1 (4.1)	12.1 (4.6)
		Minimum	-13.0 (3.4)	-12.2 (2.7)	-12.6 (3.2)
Angle (degrees) – Frontal Plane	Hip	Maximum	2.9 (2.3)	2.7 (1.8)	3.0 (2.3)
		Minimum	-6.6 (2.9)	-6.7 (2.1)	-6.1 (2.8)
	Knee	Maximum	8.4 (3.6)	6.5 (3.1)	7.8 (5.0)
		Minimum	-2.6 (3.6)	-3.3 (3.1)	-2.7 (3.4)
	Ankle	Maximum	7.6 (3.6)	5.8 (3.5)	3.7 (3.8)
		Minimum	-6.5 (3.3)	-7.7 (2.8)	-8.3 (3.6)
Angle (degrees) – Transverse Plane	Hip	Maximum	-2.4 (5.4)	-1.7 (5.9)	-2.5 (7.5)
		Minimum	-12.2 (3.9)	-11.3 (3.7)	-11.0 (3.7)
	Knee	Maximum	12.2 (5.2)	12.3 (5.3)	11.9 (7.5)
		Minimum	-18.1 (6.8)	-17.4 (6.4)	-19.1 (7.0)
	Ankle	Maximum	4.4 (3.3)	4.7 (3.6)	5.3 (2.5)
		Minimum	-7.2 (3.7)	-6.3 (3.6)	-5.6 (2.4)
Ground Reaction Force (N/BW)	Vertical	Maximum	1.25 (0.06)	1.27 (0.06)	1.23 (0.06)
		Minimum	0.06 (0.03)	0.05 (0.02)	0.07 (0.06)
	Anterior-Posterior	Maximum	0.24 (0.03)	0.23 (0.03)	0.21 (0.03)
		Minimum	-0.19 (0.03)	-0.18 (0.04)	-0.17 (0.04)
	Medial-Lateral	Maximum	0.11 (0.05)	0.10 (0.02)	0.10 (0.01)
		Minimum	-0.02 (0.01)	-0.02 (0.01)	-0.04 (0.01)

Note: Values given as mean (s.d.), N=12

Positive values indicate flexion, adduction, and external rotation; upward, posterior and medial GRF

Negative values indicate extension, abduction and internal rotation; downward, anterior and lateral GRF

Table C-1b. Joint moments and powers for walking.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
Moment (Nm/kg)	Sagital Plane	Hip	Maximum	0.90 (0.20)	1.04 (0.25)	0.90 (0.32)
			Minimum	-0.99 (0.17)	-1.00 (0.21)	-1.00 (0.27)
		Knee	Maximum	0.62 (0.14)	0.58 (0.13)	0.60 (0.17)
			Minimum	-0.47 (0.14)	-0.47 (0.14)	-0.47 (0.12)
		Ankle	Maximum	1.76 (0.15)	1.88 (0.19)	1.84 (0.16)
			Minimum	-0.41 (0.08)	-0.42 (0.08)	-0.43 (0.07)
	Frontal Plane	Hip	Maximum	1.04 (0.45)	0.89 (0.11)	0.89 (0.15)
			Minimum	-0.17 (0.07)	-0.18 (0.07)	-0.17 (0.08)
		Knee	Maximum	0.46 (0.33)	0.37 (0.12)	0.33 (0.12)
			Minimum	-0.14 (0.06)	-0.13 (0.06)	-0.14 (0.08)
		Ankle	Maximum	0.20 (0.12)	0.23 (0.15)	0.24 (0.16)
			Minimum	-0.10 (0.22)	-0.03 (0.03)	-0.02 (0.03)
	Transverse Plane	Hip	Maximum	0.21 (0.25)	0.12 (0.03)	0.11 (0.05)
			Minimum	-0.11 (0.03)	-0.10 (0.05)	-0.09 (0.04)
		Knee	Maximum	0.09 (0.02)	0.09 (0.03)	0.10 (0.02)
			Minimum	-0.08 (0.18)	-0.03 (0.02)	-0.04 (0.01)
		Ankle	Maximum	0.04 (0.02)	0.04 (0.02)	0.05 (0.03)
			Minimum	-0.22 (0.04)	-0.23 (0.05)	-0.25 (0.05)
Power (W/kg)	Sagital Plane	Hip	Maximum	1.41 (0.52)	1.36 (0.46)	1.25 (0.52)
			Minimum	-0.82 (0.22)	-0.85 (0.28)	-0.80 (0.25)
		Knee	Maximum	0.79 (0.26)	0.80 (0.21)	0.77 (0.18)
			Minimum	-1.48 (0.66)	-1.21 (0.46)	-1.00 (0.39)
		Ankle	Maximum	2.34 (0.66)	2.33 (0.59)	2.36 (0.71)
			Minimum	-1.16 (0.51)	-1.37 (0.47)	-1.31 (0.38)
	Frontal Plane	Hip	Maximum	0.73 (0.82)	0.47 (0.13)	0.42 (0.15)
			Minimum	-0.35 (0.20)	-0.30 (0.18)	-0.25 (0.11)
		Knee	Maximum	0.12 (0.08)	0.11 (0.07)	0.08 (0.04)
			Minimum	-0.37 (0.52)	-0.17 (0.07)	-0.14 (0.06)
		Ankle	Maximum	0.27 (0.25)	0.27 (0.28)	0.30 (0.26)
			Minimum	-0.14 (0.08)	-0.09 (0.05)	-0.08 (0.07)
	Transverse Plane	Hip	Maximum	0.07 (0.05	0.07 (0.05	0.06 (0.03
			Minimum	-0.13 (0.12)	-0.10 (0.04)	-0.08 (0.05)
		Knee	Maximum	0.05 (0.03)	0.05 (0.02)	0.06 (0.03)
			Minimum	-0.06 (0.07)	-0.06 (0.02)	-0.06 (0.03)
		Ankle	Maximum	0.05 (0.04)	0.04 (0.03)	0.05 (0.05)
			Minimum	-0.07 (0.04)	-0.07 (0.04)	-0.09 (0.05)

Note: Values given as mean (s.d.), N=12

Positive values indicate extensor, abductor, and internal rotator moment; and power generation

Negative values indicate flexor, adductor, and external rotator moment; and power absorption

Table C-2a. Temporal-spatial variables, joint angles and ground reaction forces for running.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
	Stride Length (m)			2.450 (0.281)	2.361 (0.388)	2.436 (0.284)
	Stride Time (s)			0.794 (0.035)	0.786 (0.063)	0.797 (0.047)
	Velocity (m/s)			3.084 (0.317)	2.995 (0.355)	3.059 (0.347)
	% Stance			34.3 (2.8)	37.6 (3.5)	36.8 (2.4)
Angle (degrees)	Sagittal Plane	Hip	Maximum	35.6 (8.0)	36.3 (7.2)	36.1 (7.6)
			Minimum	-28.1 (5.9)	-27.0 (4.3)	-28.3 (5.7)
		Knee	Maximum	91.9 (10.9)	93.8 (11.6)	90.3 (12.1)
			Minimum	6.3 (5.1)	8.4 (5.7)	5.9 (5.0)
		Ankle	Maximum	20.9 (3.6)	22.9 (3.7)	22.8 (3.8)
			Minimum	-15.1 (4.2)	-11.3 (5.8)	-12.9 (3.8)
	Frontal Plane	Hip	Maximum	4.6 (1.8)	4.1 (1.2)	4.6 (1.9)
			Minimum	-5.3 (2.5)	-5.7 (2.6)	-5.7 (3.1)
		Knee	Maximum	7.0 (4.5)	6.2 (3.2)	7.7 (5.7)
			Minimum	-2.4 (3.1)	-3.8 (4.3)	-4.4 (5.1)
		Ankle	Maximum	7.9 (3.8)	6.4 (3.6)	7.6 (7.6)
			Minimum	-11.9 (3.7)	-13.7 (3.4)	-14.7 (5.0)
	Transverse Plane	Hip	Maximum	2.8 (5.9)	3.0 (6.9)	2.4 (7.1)
			Minimum	-16.1 (7.1)	-15.2 (6.6)	-16.1 (8.7)
		Knee	Maximum	11.9 (4.9)	10.0 (4.9)	11.0 (6.3)
			Minimum	-6.4 (4.1)	-5.9 (4.9)	-5.6 (5.6)
		Ankle	Maximum	6.5 (4.2)	6.4 (4.9)	7.1 (2.9)
			Minimum	-4.0 (3.4)	-3.1 (5.0)	-2.7 (2.6)
Ground Reaction Force (N/BW)		Vertical	Maximum	2.42 (0.20)	2.42 (0.17)	2.40 (0.18)
			Minimum	0.04 (0.04)	0.04 (0.04)	0.02 (0.03)
		Anterior-Posterior	Maximum	0.26 (0.03)	0.25 (0.04)	0.24 (0.04)
			Minimum	-0.23 (0.07)	-0.19 (0.07)	-0.20 (0.07)
		Medial-Lateral	Maximum	0.23 (0.05)	0.23 (0.04)	0.22 (0.04)
			Minimum	-0.00 (0.01)	-0.00 (0.01)	-0.01 (0.01)

Note: Values given as mean (s.d.), N=12

Positive values indicate flexion, adduction, and external rotation; upward, posterior and medial GRF

Negative values indicate extension, abduction and internal rotation; downward, anterior and lateral GRF

Table C-2b. Joint moments and powers for running.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
Moment (Nm/kg)	Sagital Plane	Hip	Maximum	1.08 (0.24)	1.30 (0.72)	1.22 (0.61)
			Minimum	-0.82 (0.17)	-0.87 (0.18)	-0.95 (0.15)
		Knee	Maximum	2.38 (0.50)	2.32 (0.63)	2.40 (0.49)
			Minimum	-0.39 (0.07)	-0.39 (0.06)	-0.37 (0.06)
		Ankle	Maximum	2.67 (0.29)	2.83 (0.33)	2.74 (0.37)
			Minimum	-0.29 (0.12)	-0.31 (0.16)	-0.34 (0.14)
	Frontal Plane	Hip	Maximum	1.51 (0.36)	1.42 (0.28)	1.44 (0.36)
			Minimum	-0.18 (0.08)	-0.19 (0.09)	-0.18 (0.11)
		Knee	Maximum	0.96 (0.48)	0.89 (0.49)	0.93 (0.40)
			Minimum	-0.11 (0.08)	-0.11 (0.08)	-0.11 (0.05)
		Ankle	Maximum	0.51 (0.31)	0.47 (0.28)	0.58 (0.38)
			Minimum	-0.03 (0.02)	-0.03 (0.03)	-0.03 (0.03)
	Transverse Plane	Hip	Maximum	0.09 (0.05)	0.10 (0.05)	0.09 (0.05)
			Minimum	-0.13 (0.05)	-0.15 (0.09)	-0.13 (0.07)
		Knee	Maximum	0.06 (0.04)	0.06 (0.03)	0.06 (0.02)
			Minimum	-0.19 (0.07)	-0.23 (0.04)	-0.21 (0.06)
		Ankle	Maximum	0.05 (0.04)	0.04 (0.04)	0.04 (0.03)
			Minimum	-0.31 (0.05)	-0.31 (0.09)	-0.31 (0.06)
Power (W/kg)	Sagital Plane	Hip	Maximum	3.00 (0.91)	2.84 (1.13)	3.00 (1.21)
			Minimum	-1.71 (0.70)	-1.65 (0.61)	-2.31 (1.12)
		Knee	Maximum	3.80 (1.51)	4.31 (1.64)	4.22 (1.77)
			Minimum	-6.91 (1.54)	-6.61 (2.74)	-6.50 (2.13)
		Ankle	Maximum	8.39 (1.12)	8.46 (0.97)	8.13 (1.41)
			Minimum	-5.13 (0.71)	-5.52 (0.73)	-5.57 (1.31)
	Frontal Plane	Hip	Maximum	0.46 (0.38)	0.47 (0.39)	0.64 (0.62)
			Minimum	-1.06 (0.64)	-0.89 (0.59)	-0.99 (0.51)
		Knee	Maximum	1.00 (0.96)	0.97 (0.98)	0.93 (0.86)
			Minimum	-0.70 (0.63)	-0.62 (0.62)	-0.77 (0.60)
		Ankle	Maximum	0.71 (0.70)	0.63 (0.57)	0.98 (0.93)
			Minimum	-0.46 (0.40)	-0.38 (0.40)	-0.69 (0.69)
	Transverse Plane	Hip	Maximum	0.16 (0.11)	0.20 (0.18)	0.16 (0.10)
			Minimum	-0.12 (0.09)	-0.08 (0.05)	-0.10 (0.07)
		Knee	Maximum	0.22 (0.16)	0.20 (0.13)	0.21 (0.21)
			Minimum	-0.05 (0.05)	-0.08 (0.06)	-0.07 (0.05)
		Ankle	Maximum	0.05 (0.03)	0.06 (0.08)	0.07 (0.06)
			Minimum	-0.21 (0.10)	-0.19 (0.08)	-0.17 (0.09)

Note: Values given as mean (s.d.), N=12

Positive values indicate extensor, abductor, and internal rotator moment; and power generation

Negative values indicate flexor, adductor, and external rotator moment; and power absorption

Table C-3a. Cycle time, joint angles, and ground reaction forces for squatting.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
Cycle Time (s)				3.079 (0.466)	3.143 (0.470)	3.056 (0.537)
Angle (degrees)	Sagittal Plane	Hip	Maximum	93.9 (9.9)	95.4 (8.6)	93.9 (9.8)
			Minimum	-5.1 (2.2)	-3.7 (2.4)	-5.6 (3.2)
		Knee	Maximum	131.1 (9.2)	130.5 (9.7)	128.4 (10.0)
			Minimum	-5.0 (4.2)	-3.0 (3.2)	-4.1 (4.6)
		Ankle	Maximum	29.2 (4.9)	29.1 (4.9)	28.2 (4.7)
			Minimum	-2.7 (3.0)	-2.4 (2.8)	-2.4 (3.5)
	Frontal Plane	Hip	Maximum	-2.3 (2.5)	-2.3 (2.1)	-2.1 (2.2)
			Minimum	-25.4 (7.2)	-25.1 (8.7)	-24.7 (9.2)
		Knee	Maximum	3.4 (2.8)	3.1 (3.2)	4.9 (6.4)
			Minimum	-14.3 (6.3)	-16.8 (10.3)	-15.8 (11.6)
		Ankle	Maximum	2.9 (2.6)	2.2 (1.9)	1.1 (2.6)
			Minimum	-15.5 (4.9)	-16.8 (5.8)	-16.4 (5.7)
	Transverse Plane	Hip	Maximum	-9.3 (5.2)	-7.9 (3.8)	-9.0 (6.0)
			Minimum	-18.0 (4.4)	-17.1 (4.1)	-17.6 (5.2)
		Knee	Maximum	6.3 (4.8)	6.2 (4.8)	7.0 (5.4)
			Minimum	-5.3 (5.1)	-4.2 (5.9)	-5.0 (4.8)
		Ankle	Maximum	6.9 (3.4)	7.2 (4.8)	8.4 (3.4)
			Minimum	-3.1 (3.7)	-3.3 (3.7)	-1.3 (3.5)
Ground Reaction Force (N/BW)		Vertical	Maximum	0.63 (0.05)	0.63 (0.05)	0.63 (0.04)
			Minimum	0.40 (0.05)	0.40 (0.05)	0.42 (0.04)
		Anterior-Posterior	Maximum	0.02 (0.01)	0.02 (0.01)	0.02 (0.01)
			Minimum	-0.01 (0.01)	-0.02 (0.01)	-0.02 (0.01)
		Medial-Lateral	Maximum	0.06 (0.03)	0.06 (0.01)	0.06 (0.02)
			Minimum	-0.01 (0.05)	-0.02 (0.02)	-0.02 (0.02)

Note: Values given as mean (s.d.), N=12

Positive values indicate flexion, adduction, and external rotation; upward, posterior and medial GRF

Negative values indicate extension, abduction and internal rotation; downward, anterior and lateral GRF

Table C-3b. Joint moments and powers for squatting.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
Moment (Nm/kg)	Sagital Plane	Hip	Maximum	0.73 (0.19)	0.76 (0.21)	0.76 (0.16)
			Minimum	-0.11 (0.08)	-0.08 (0.06)	-0.11 (0.12)
		Knee	Maximum	1.09 (0.17)	1.09 (0.18)	1.09 (0.14)
			Minimum	-0.11 (0.08)	-0.09 (0.08)	-0.10 (0.14)
		Ankle	Maximum	0.34 (0.16)	0.36 (0.18)	0.34 (0.16)
			Minimum	-0.02 (0.08)	-0.05 (0.12)	-0.03 (0.12)
	Frontal Plane	Hip	Maximum	0.25 (0.36)	0.21 (0.13)	0.21 (0.15)
			Minimum	-0.37 (0.37)	-0.40 (0.16)	-0.45 (0.18)
		Knee	Maximum	0.35 (0.31)	0.26 (0.09)	0.26 (0.08)
			Minimum	-0.00 (0.21)	-0.04 (0.08)	-0.06 (0.09)
		Ankle	Maximum	0.13 (0.15)	0.15 (0.12)	0.16 (0.09)
			Minimum	-0.02 (0.09)	0.01 (0.07)	0.02 (0.05)
	Transverse Plane	Hip	Maximum	0.03 (0.09)	0.01 (0.06)	0.02 (0.03)
			Minimum	-0.07 (0.06)	-0.08 (0.06)	-0.07 (0.03)
		Knee	Maximum	0.08 (0.11)	0.09 (0.08)	0.08 (0.05)
			Minimum	-0.10 (0.18)	-0.05 (0.05)	-0.06 (0.04)
		Ankle	Maximum	0.02 (0.11)	0.01 (0.06)	0.01 (0.03)
			Minimum	-0.06 (0.07)	-0.07 (0.07)	-0.06 (0.03)
Power (W/kg)	Sagital Plane	Hip	Maximum	1.02 (0.28)	1.07 (0.31)	1.02 (0.23)
			Minimum	-0.79 (0.24)	-0.86 (0.33)	-0.85 (0.29)
		Knee	Maximum	1.91 (0.45)	1.90 (0.51)	1.80 (0.40)
			Minimum	-1.65 (0.44)	-1.53 (0.35)	-1.56 (0.40)
		Ankle	Maximum	0.11 (0.10)	0.10 (0.08)	0.10 (0.07)
			Minimum	-0.14 (0.08)	-0.15 (0.13)	-0.10 (0.05)
	Frontal Plane	Hip	Maximum	0.28 (0.13)	0.18 (0.08)	0.21 (0.13)
			Minimum	-0.28 (0.21)	-0.20 (0.07)	-0.21 (0.12)
		Knee	Maximum	0.28 (0.30)	0.21 (0.10)	0.19 (0.09)
			Minimum	-0.22 (0.19)	-0.14 (0.10)	-0.16 (0.07)
		Ankle	Maximum	0.03 (0.03)	0.04 (0.03)	0.03 (0.03)
			Minimum	-0.04 (0.04)	-0.04 (0.03)	-0.03 (0.02)
	Transverse Plane	Hip	Maximum	0.03 (0.01)	0.02 (0.01)	0.02 (0.01)
			Minimum	-0.02 (0.01)	-0.02 (0.01)	-0.01 (0.01)
		Knee	Maximum	0.04 (0.06)	0.02 (0.02)	0.02 (0.01)
			Minimum	-0.03 (0.05)	-0.02 (0.02)	-0.02 (0.01)
		Ankle	Maximum	0.01 (0.02)	0.01 (0.01)	0.01 (0.00)
			Minimum	-0.01 (0.02)	-0.01 (0.01)	-0.01 (0.01)

Note: Values given as mean (s.d.), N=12

Positive values indicate extensor, abductor, and internal rotator moment; and power generation

Negative values indicate flexor, adductor, and external rotator moment; and power absorption

Table C-4a. Cycle time, joint angles, and ground reaction forces for right kneeling.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
Cycle Time (s)				3.522 (0.393)	3.761 (0.509)	3.956 (0.305)
Angle (degrees)	Sagital Plane	Hip	Maximum	12.0 (5.2)	19.3 (9.8)	19.4 (9.3)
			Minimum	-8.1 (4.6)	-6.5 (3.1)	-7.8 (3.3)
		Knee	Maximum	119.6 (9.7)	131.7 (14.9)	130.1 (14.7)
			Minimum	-0.1 (5.0)	1.3 (4.2)	-0.3 (5.9)
		Ankle	Maximum	33.3 (5.2)	35.1 (6.7)	35.8 (5.6)
			Minimum	2.9 (2.4)	1.5 (3.7)	1.3 (3.6)
	Frontal Plane	Hip	Maximum	2.8 (2.1)	2.0 (2.4)	2.8 (2.6)
			Minimum	-12.3 (4.1)	-12.3 (3.9)	-11.3 (2.9)
		Knee	Maximum	14.2 (9.8)	11.9 (6.7)	13.4 (8.0)
			Minimum	-0.7 (3.6)	-3.2 (5.6)	-2.6 (5.7)
		Ankle	Maximum	8.5 (4.6)	4.5 (5.8)	3.1 (4.6)
			Minimum	-12.8 (4.1)	-14.3 (5.4)	-17.0 (6.9)
	Transverse Plane	Hip	Maximum	-3.5 (5.0)	0.3 (6.5)	0.8 (4.7)
			Minimum	-17.7 (5.1)	-19.0 (7.6)	-20.4 (6.8)
		Knee	Maximum	4.9 (3.9)	5.7 (4.0)	5.6 (3.4)
			Minimum	-6.4 (3.8)	-7.2 (6.6)	-7.8 (7.3)
		Ankle	Maximum	7.1 (2.7)	9.1 (5.5)	11.5 (5.4)
			Minimum	-13.7 (6.6)	-9.1 (6.0)	-8.6 (6.2)
Ground Reaction Force (N/BW)		Vertical	Maximum	1.01 (0.04)	1.02 (0.03)	1.04 (0.03)
			Minimum	0.24 (0.06)	0.22 (0.05)	0.20 (0.05)
		Anterior-Posterior	Maximum	0.15 (0.02)	0.14 (0.02)	0.14 (0.02)
			Minimum	-0.01 (0.01)	0.00 (0.01)	-0.01 (0.02)
		Medial-Lateral	Maximum	0.10 (0.02)	0.10 (0.01)	0.10 (0.02)
			Minimum	-0.00 (0.01)	0.00 (0.01)	0.00 (0.01)

Note: Values given as mean (s.d.), N=12

Positive values indicate flexion, adduction, and external rotation; upward, posterior and medial GRF

Negative values indicate extension, abduction and internal rotation; downward, anterior and lateral GRF

Table C-4b. Joint moments and powers for right kneeling.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
Moment (Nm/kg)	Sagital Plane	Hip	Maximum	0.17 (0.23)	0.22 (0.22)	0.14 (0.22)
			Minimum	-1.18 (0.16)	-1.08 (0.26)	-1.14 (0.23)
		Knee	Maximum	1.38 (0.18)	1.60 (0.27)	1.71 (0.24)
			Minimum	-0.12 (0.26)	-0.09 (0.13)	-0.04 (0.13)
		Ankle	Maximum	1.20 (0.20)	1.24 (0.18)	1.18 (0.23)
			Minimum	-0.15 (0.14)	-0.25 (0.15)	-0.34 (0.11)
	Frontal Plane	Hip	Maximum	0.91 (0.21)	0.89 (0.11)	0.92 (0.13)
			Minimum	-0.18 (0.08)	-0.14 (0.13)	-0.16 (0.12)
		Knee	Maximum	0.54 (0.14)	0.57 (0.10)	0.57 (0.14)
			Minimum	-0.08 (0.05)	-0.13 (0.10)	-0.17 (0.12)
		Ankle	Maximum	0.23 (0.13)	0.28 (0.18)	0.27 (0.11)
			Minimum	-0.07 (0.09)	-0.05 (0.08)	-0.04 (0.05)
	Transverse Plane	Hip	Maximum	0.12 (0.07)	0.11 (0.06)	0.11 (0.03)
			Minimum	-0.06 (0.06)	-0.04 (0.06)	-0.04 (0.03)
		Knee	Maximum	0.06 (0.06)	0.03 (0.06)	0.03 (0.02)
			Minimum	-0.13 (0.08)	-0.18 (0.08)	-0.17 (0.05)
		Ankle	Maximum	0.02 (0.06)	0.02 (0.05)	0.03 (0.02)
			Minimum	-0.20 (0.04)	-0.20 (0.09)	-0.21 (0.04)
Power (W/kg)	Sagital Plane	Hip	Maximum	0.41 (0.15)	0.41 (0.16)	0.51 (0.15)
			Minimum	-0.34 (0.22)	-0.37 (0.22)	-0.48 (0.28)
		Knee	Maximum	2.73 (0.44)	2.46 (1.00)	2.45 (1.00)
			Minimum	-2.58 (0.93)	-2.35 (0.83)	-2.41 (0.63)
		Ankle	Maximum	0.91 (0.14)	0.91 (0.17)	0.91 (0.17)
			Minimum	-1.02 (0.17)	-1.02 (0.21)	-0.95 (0.14)
	Frontal Plane	Hip	Maximum	0.28 (0.15)	0.27 (0.10)	0.25 (0.09)
			Minimum	-0.39 (0.11)	-0.36 (0.15)	-0.33 (0.14)
		Knee	Maximum	0.36 (0.19)	0.40 (0.32)	0.30 (0.20)
			Minimum	-0.18 (0.13)	-0.21 (0.13)	-0.17 (0.09)
		Ankle	Maximum	0.08 (0.04)	0.12 (0.06)	0.10 (0.04)
			Minimum	-0.12 (0.08)	-0.09 (0.10)	-0.12 (0.08)
	Transverse Plane	Hip	Maximum	0.04 (0.04)	0.05 (0.03)	0.05 (0.02)
			Minimum	-0.03 (0.03)	-0.04 (0.02)	-0.04 (0.02)
		Knee	Maximum	0.04 (0.06)	0.05 (0.03)	0.06 (0.05)
			Minimum	-0.04 (0.05)	-0.06 (0.04)	-0.06 (0.04)
		Ankle	Maximum	0.06 (0.06)	0.07 (0.04)	0.05 (0.03)
			Minimum	-0.04 (0.04)	-0.05 (0.02)	-0.04 (0.02)

Note: Values given as mean (s.d.), N=12

Positive values indicate extensor, abductor, and internal rotator moment; and power generation

Negative values indicate flexor, adductor, and external rotator moment; and power absorption

Table C-5a. Cycle time, joint angles, and ground reaction forces for left kneeling.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
Cycle Time (s)				3.292 (0.421)	3.462 (0.393)	3.522 (0.444)
Angle (degrees)	Sagital Plane	Hip	Maximum	95.2 (6.3)	98.4 (5.4)	102.4 (9.8)
			Minimum	-2.5 (4.9)	-0.7 (2.0)	-1.9 (4.7)
		Knee	Maximum	119.1 (8.3)	123.6 (5.9)	128.7 (7.7)
			Minimum	3.6 (6.9)	4.5 (2.9)	3.1 (6.4)
		Ankle	Maximum	21.2 (7.2)	22.8 (4.9)	24.2 (4.7)
			Minimum	-0.3 (2.6)	-0.1 (2.4)	-0.9 (2.4)
	Frontal Plane	Hip	Maximum	2.2 (2.3)	1.5 (2.5)	2.4 (3.0)
			Minimum	-18.7 (6.0)	-24.0 (5.8)	-23.5 (5.5)
		Knee	Maximum	4.9 (3.9)	3.5 (1.9)	4.9 (5.2)
			Minimum	-10.2 (5.1)	-15.3 (6.2)	-15.5 (7.6)
		Ankle	Maximum	-0.4 (3.3)	-1.1 (2.5)	-1.2 (2.5)
			Minimum	-15.4 (4.8)	-17.3 (4.2)	-18.3 (4.1)
	Transverse Plane	Hip	Maximum	-2.4 (4.5)	-3.7 (5.8)	-4.3 (7.3)
			Minimum	-15.6 (3.6)	-17.0 (4.9)	-18.4 (6.9)
		Knee	Maximum	4.6 (3.0)	7.5 (4.3)	7.1 (5.1)
			Minimum	-5.8 (3.4)	-2.6 (3.7)	-3.7 (5.8)
		Ankle	Maximum	8.3 (3.9)	9.5 (3.0)	10.9 (3.7)
			Minimum	-2.2 (3.5)	-1.9 (2.9)	-1.5 (3.0)
Ground Reaction Force (N/BW)		Vertical	Maximum	1.02 (0.04)	1.02 (0.06)	1.03 (0.04)
			Minimum	0.27 (0.07)	0.27 (0.08)	0.24 (0.08)
		Anterior-Posterior	Maximum	0.02 (0.01)	0.03 (0.02)	0.02 (0.03)
			Minimum	-0.09 (0.04)	-0.10 (0.03)	-0.09 (0.04)
		Medial-Lateral	Maximum	0.09 (0.02)	0.09 (0.01)	0.08 (0.01)
			Minimum	-0.00 (0.02)	-0.00 (0.02)	-0.01 (0.02)

Note: Values given as mean (s.d.), N=12

Positive values indicate flexion, adduction, and external rotation; upward, posterior and medial GRF

Negative values indicate extension, abduction and internal rotation; downward, anterior and lateral GRF

Table C-5b. Joint moments and powers for left kneeling.

Variable				Sole Condition		
				Baseline	1-inch Sole	2-inch Sole
Moment (Nm/kg)	Sagital Plane	Hip	Maximum	1.34 (0.32)	1.46 (0.28)	1.42 (0.25)
			Minimum	-0.25 (0.17)	-0.17 (0.14)	-0.24 (0.18)
		Knee	Maximum	1.27 (0.13)	1.35 (0.16)	1.41 (0.09)
			Minimum	0.01 (0.11)	-0.01 (0.11)	0.02 (0.12)
		Ankle	Maximum	0.59 (0.22)	0.61 (0.19)	0.57 (0.19)
			Minimum	-0.07 (0.09)	-0.04 (0.08)	-0.10 (0.13)
	Frontal Plane	Hip	Maximum	0.82 (0.26)	0.73 (0.12)	0.73 (0.16)
			Minimum	-0.34 (0.19)	-0.34 (0.18)	-0.31 (0.22)
		Knee	Maximum	0.49 (0.16)	0.55 (0.18)	0.56 (0.15)
			Minimum	-0.07 (0.14)	-0.09 (0.10)	-0.06 (0.07)
		Ankle	Maximum	0.13 (0.08)	0.23 (0.07)	0.23 (0.10)
			Minimum	-0.05 (0.11)	-0.00 (0.06)	-0.01 (0.05)
	Transverse Plane	Hip	Maximum	0.03 (0.10)	0.01 (0.02)	0.03 (0.02)
			Minimum	-0.15 (0.05)	-0.18 (0.05)	-0.16 (0.05)
		Knee	Maximum	0.09 (0.03)	0.10 (0.03)	0.10 (0.04)
			Minimum	-0.11 (0.06)	-0.10 (0.02)	-0.13 (0.03)
		Ankle	Maximum	0.05 (0.06)	0.05 (0.03)	0.07 (0.03)
			Minimum	-0.12 (0.03)	-0.12 (0.03)	-0.12 (0.03)
Power (W/kg)	Sagital Plane	Hip	Maximum	2.55 (0.78)	2.63 (0.76)	2.60 (0.81)
			Minimum	-1.84 (0.65)	-2.20 (0.61)	-2.02 (0.61)
		Knee	Maximum	2.74 (0.69)	2.70 (0.52)	3.14 (0.81)
			Minimum	-2.28 (0.96)	-2.12 (0.69)	-2.44 (0.74)
		Ankle	Maximum	0.29 (0.20)	0.36 (0.21)	0.32 (0.20)
			Minimum	-0.26 (0.18)	-0.22 (0.05)	-0.25 (0.17)
	Frontal Plane	Hip	Maximum	0.24 (0.13)	0.27 (0.09)	0.25 (0.13)
			Minimum	-0.21 (0.07)	-0.22 (0.07)	-0.26 (0.15)
		Knee	Maximum	0.23 (0.17)	0.35 (0.15)	0.42 (0.24)
			Minimum	-0.21 (0.15)	-0.33 (0.23)	-0.29 (0.15)
		Ankle	Maximum	0.05 (0.04)	0.06 (0.04)	0.06 (0.03)
			Minimum	-0.04 (0.03)	-0.05 (0.02)	-0.06 (0.04)
	Transverse Plane	Hip	Maximum	0.04 (0.02)	0.06 (0.01)	0.05 (0.04)
			Minimum	-0.06 (0.05)	-0.07 (0.03)	-0.06 (0.02)
		Knee	Maximum	0.03 (0.01)	0.04 (0.02)	0.04 (0.01)
			Minimum	-0.03 (0.01)	-0.03 (0.02)	-0.04 (0.02)
		Ankle	Maximum	0.02 (0.02)	0.02 (0.02)	0.03 (0.03)
			Minimum	-0.03 (0.02)	-0.03 (0.01)	-0.02 (0.01)

Note: Values given as mean (s.d.), N=12 for Baseline and 2-inch conditions, N=10 for 1-inch condition
Positive values indicate extensor, abductor, and internal rotator moment; and power generation
Negative values indicate flexor, adductor, and external rotator moment; and power absorption

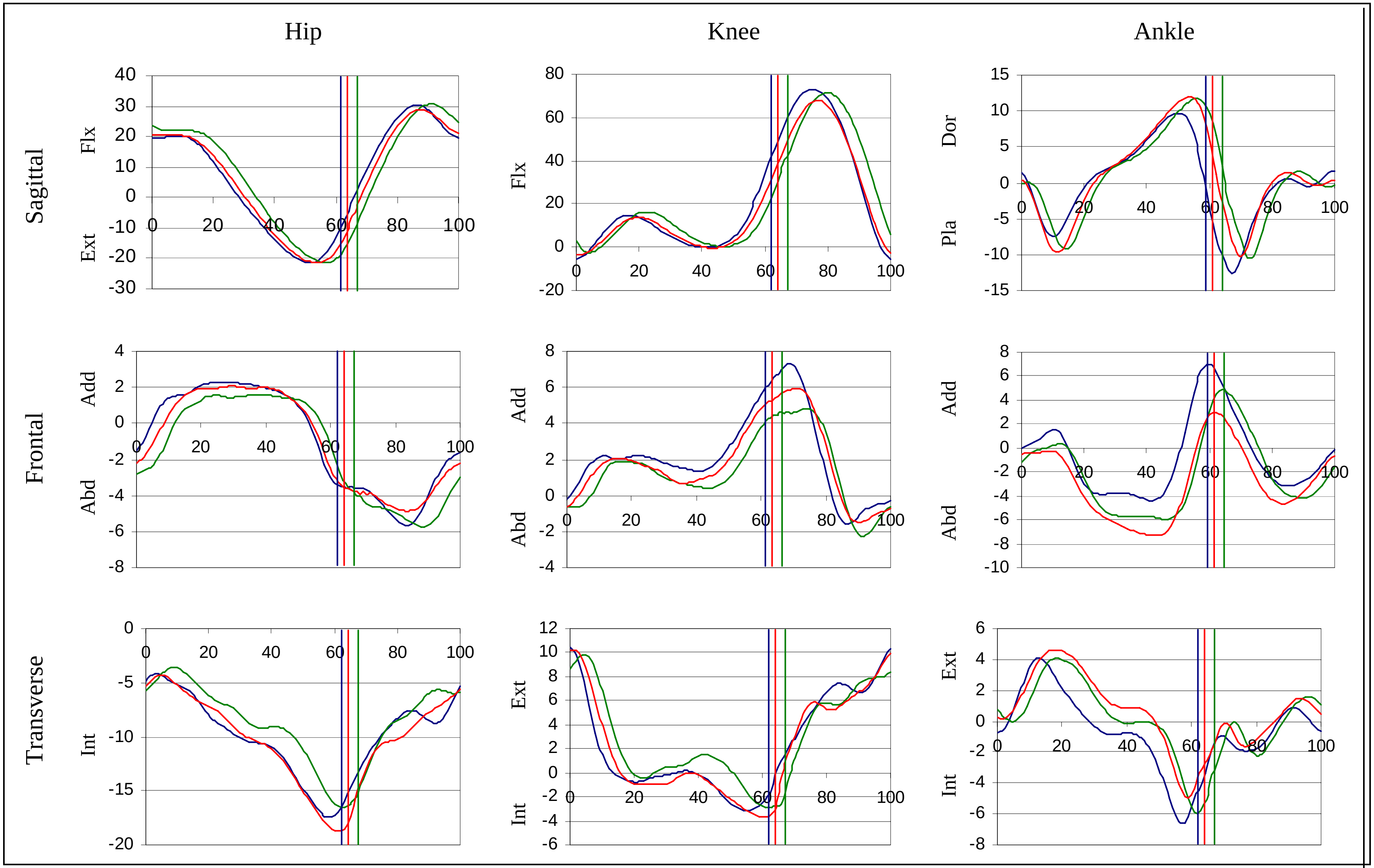

Figure D-1. Joint angles (degrees) over one stride of walking: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12, 0%=Begin Stance, vertical lines=Begin Swing, 100%= End Swing.

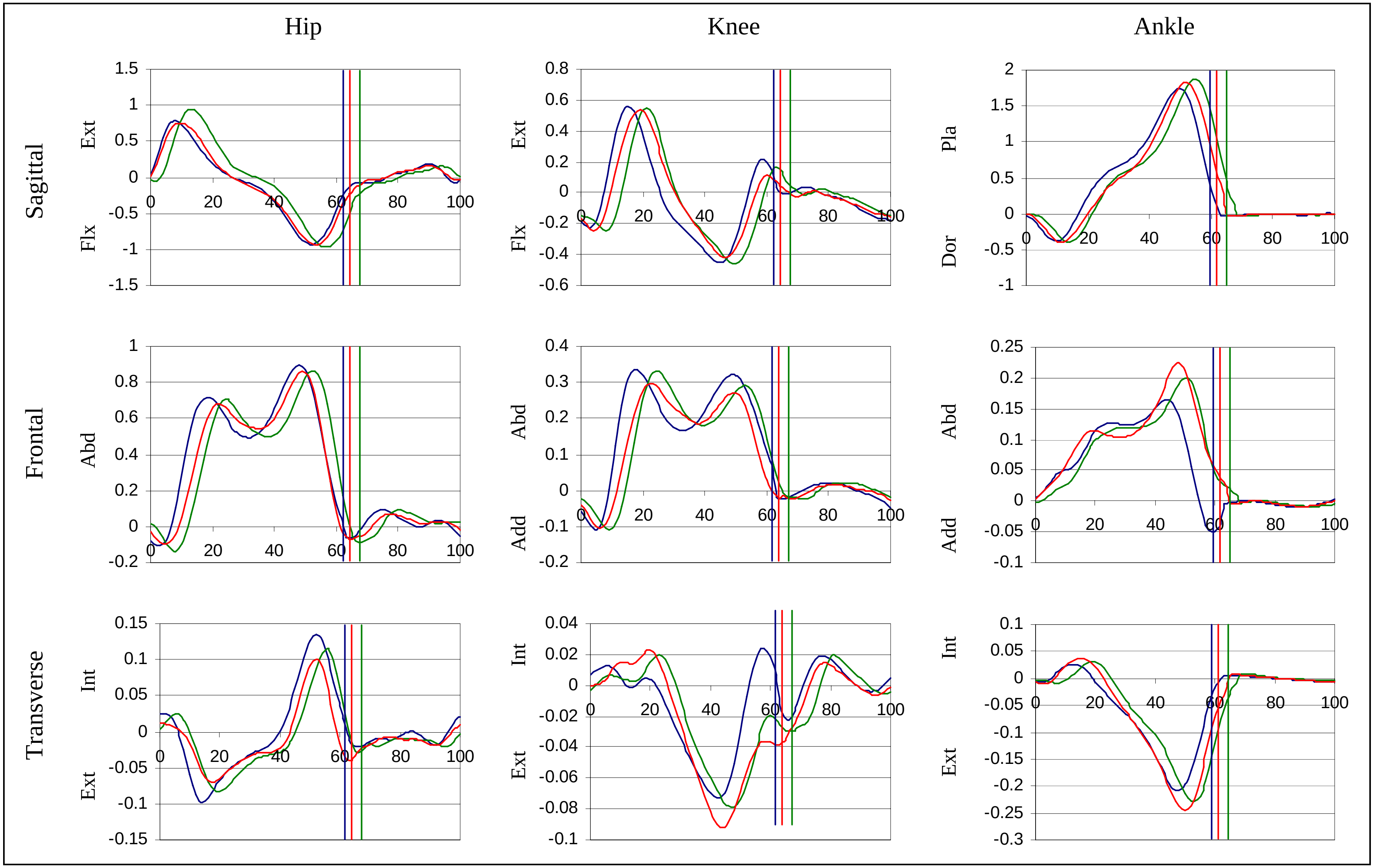

Figure D-2. Joint moments (Nm/kg) over one stride of walking: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12, 0%=Begin Stance, vertical lines=Begin Swing, 100%= End Swing.

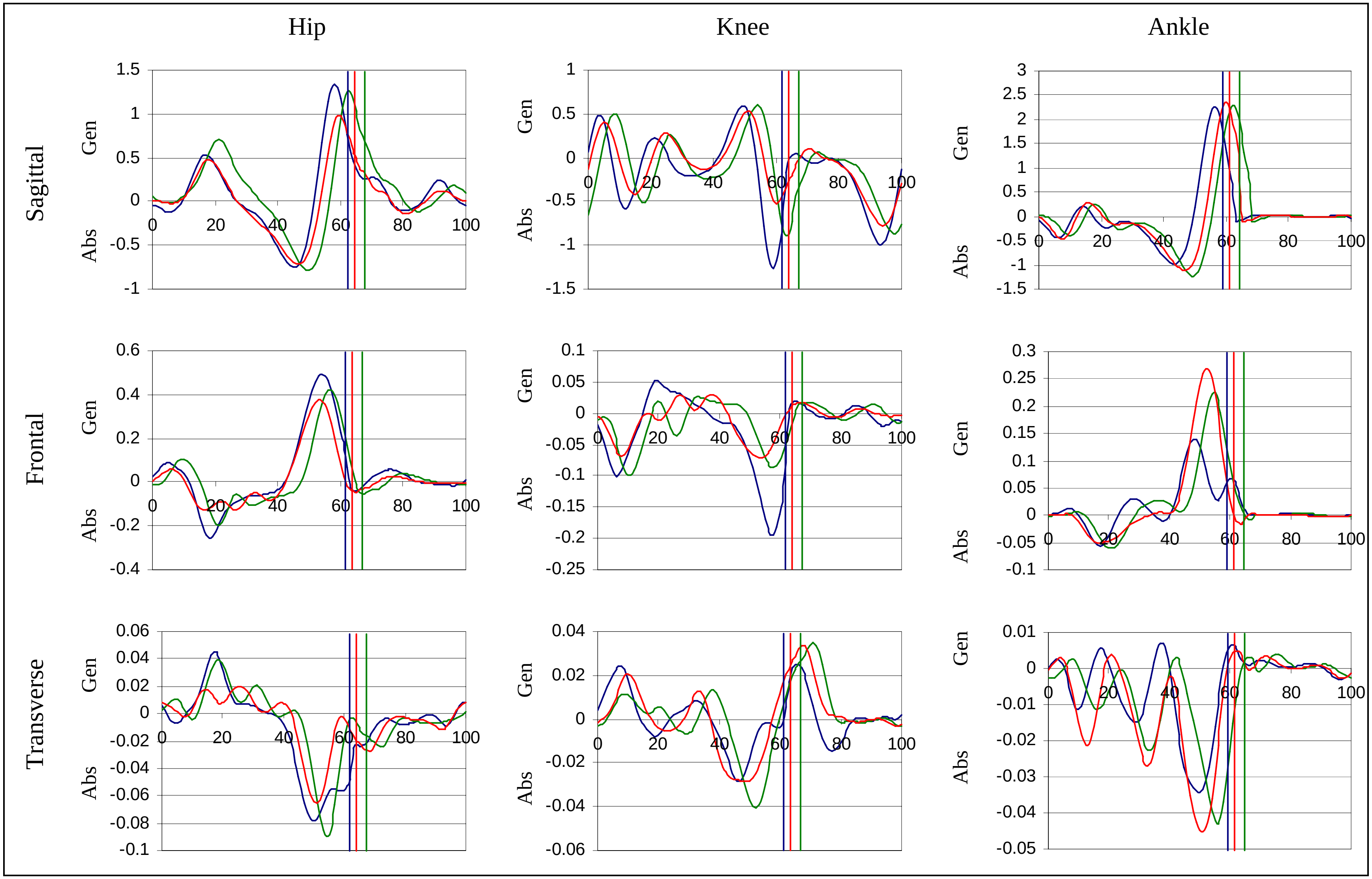

Figure D-3. Joint powers (W/kg) over one stride of walking: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12, 0%=Begin Stance, vertical lines=Begin Swing, 100%= End Swing.

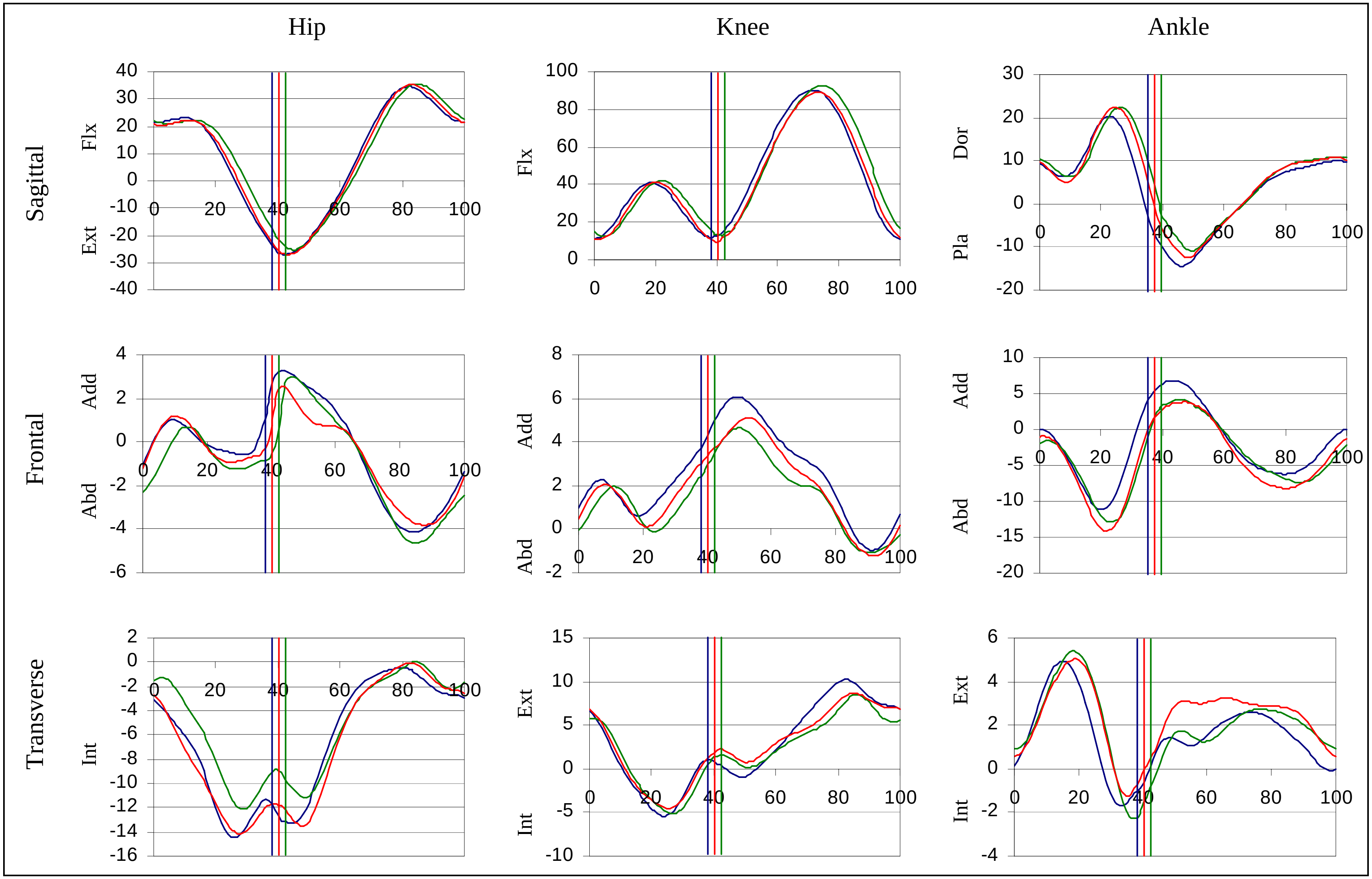

Figure D-4. Joint angles (degrees) over one stride of running: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12, 0%=Begin Stance, vertical lines=Begin Swing, 100%= End Swing.

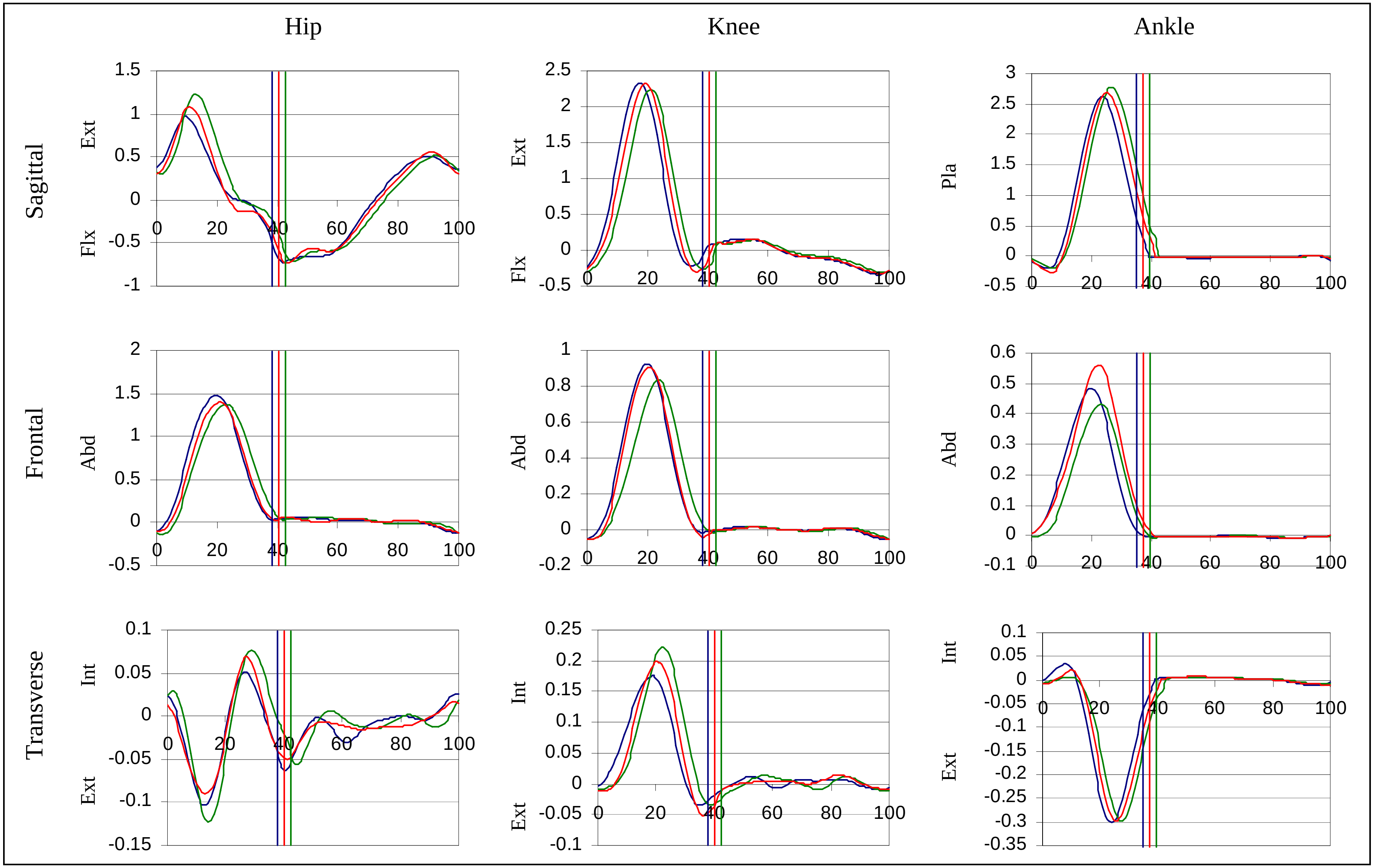

Figure D-5. Joint moments (Nm/kg) over one stride of running: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12, 0%=Begin Stance, vertical lines=Begin Swing, 100%= End Swing.

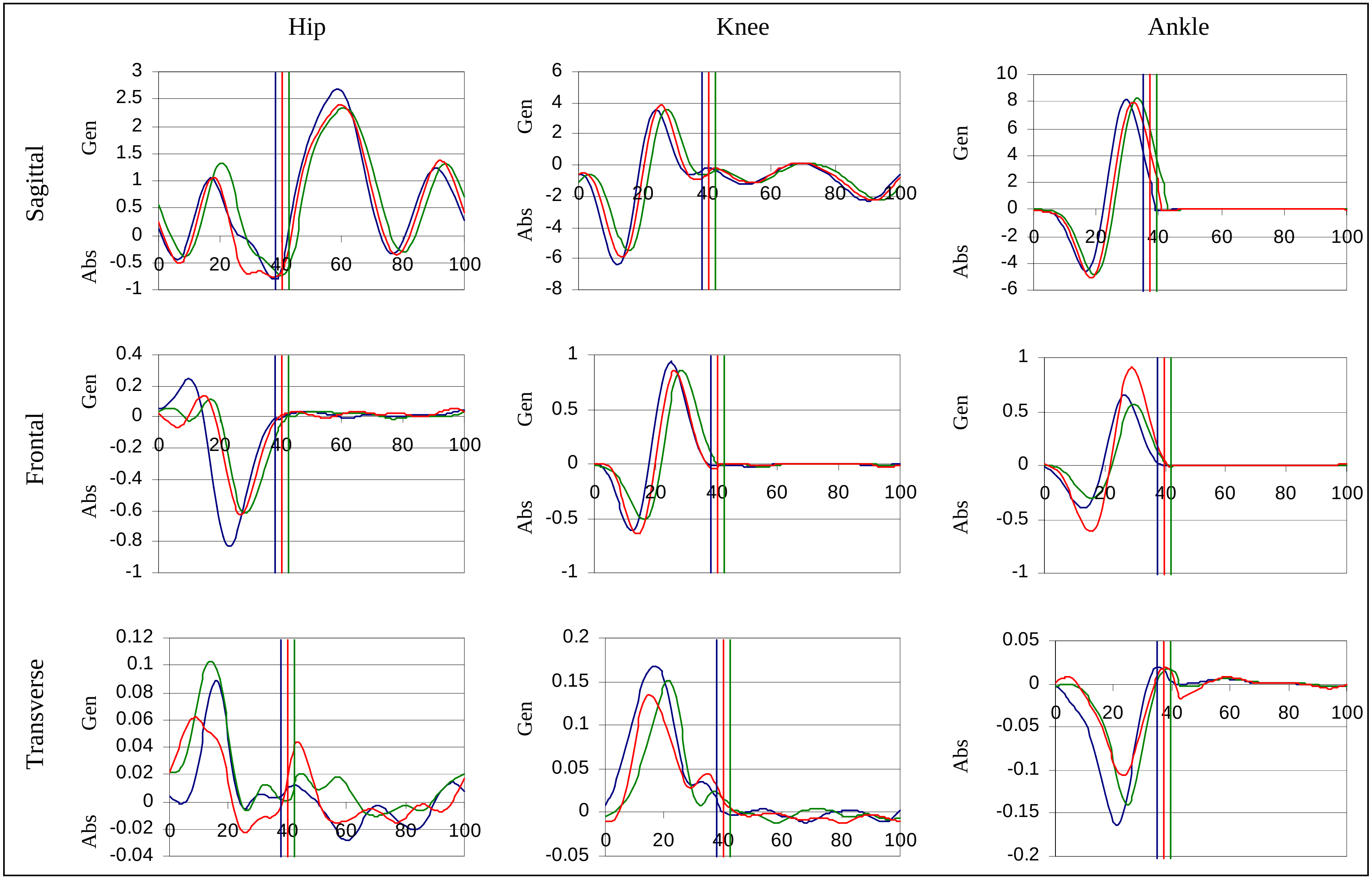

Figure D-6. Joint powers (W/kg) over one stride of running: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12, 0%=Begin Stance, vertical lines=Begin Swing, 100%= End Swing.

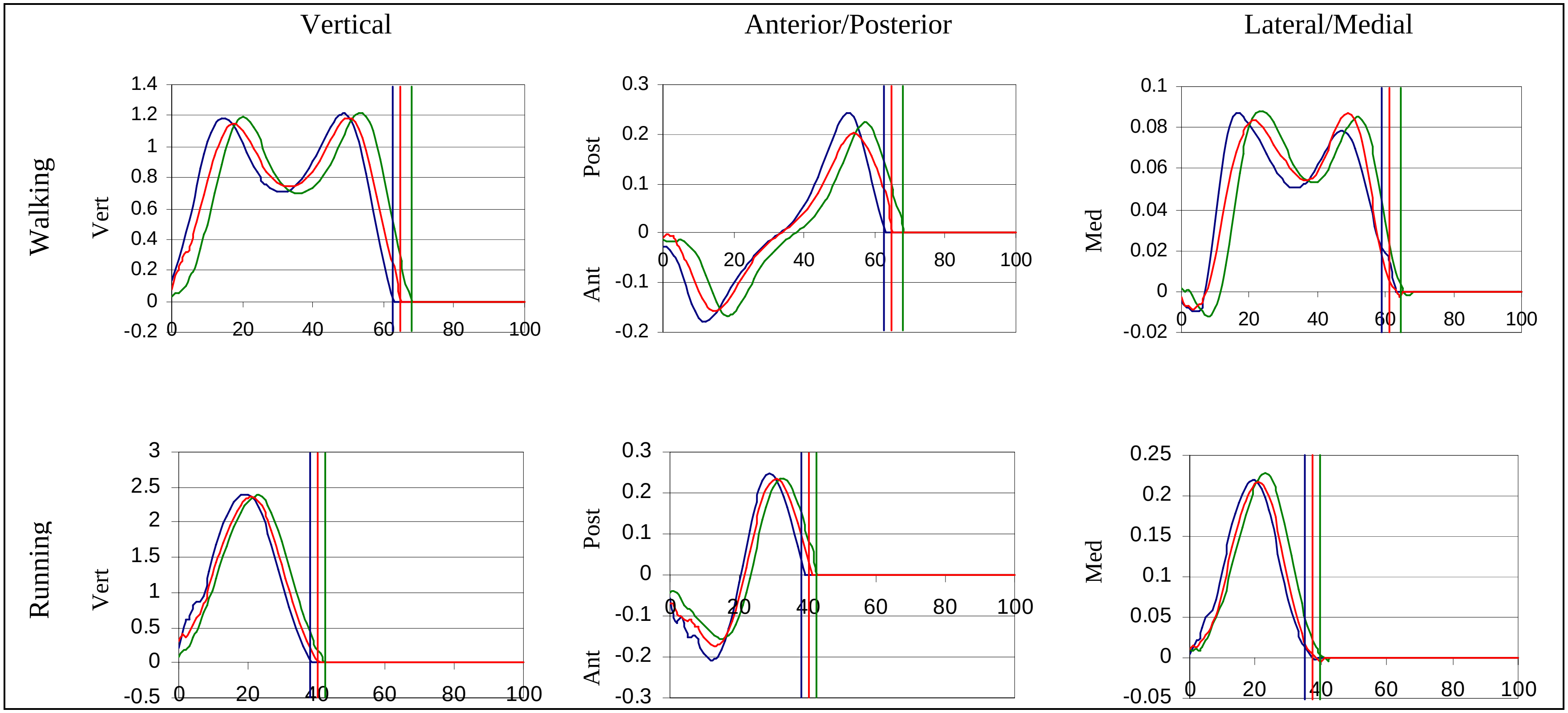

Figure D-7. Ground reaction forces (N/BW) over one stride of walking and running: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12, 0%=Begin Stance, vertical lines=Begin Swing, 100%= End Swing.

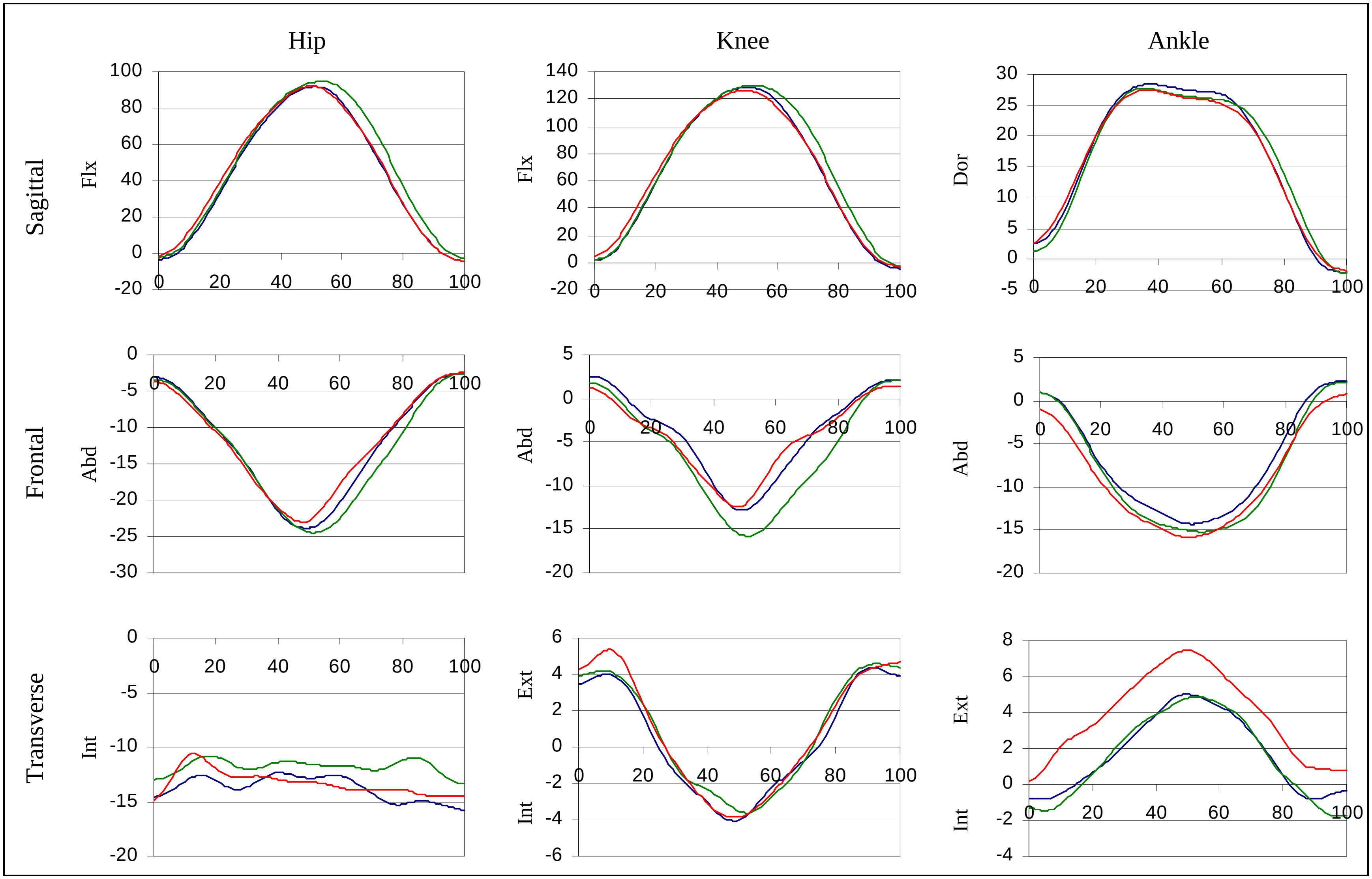

Figure D-8. Joint angles (degrees) over one cycle of squatting: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

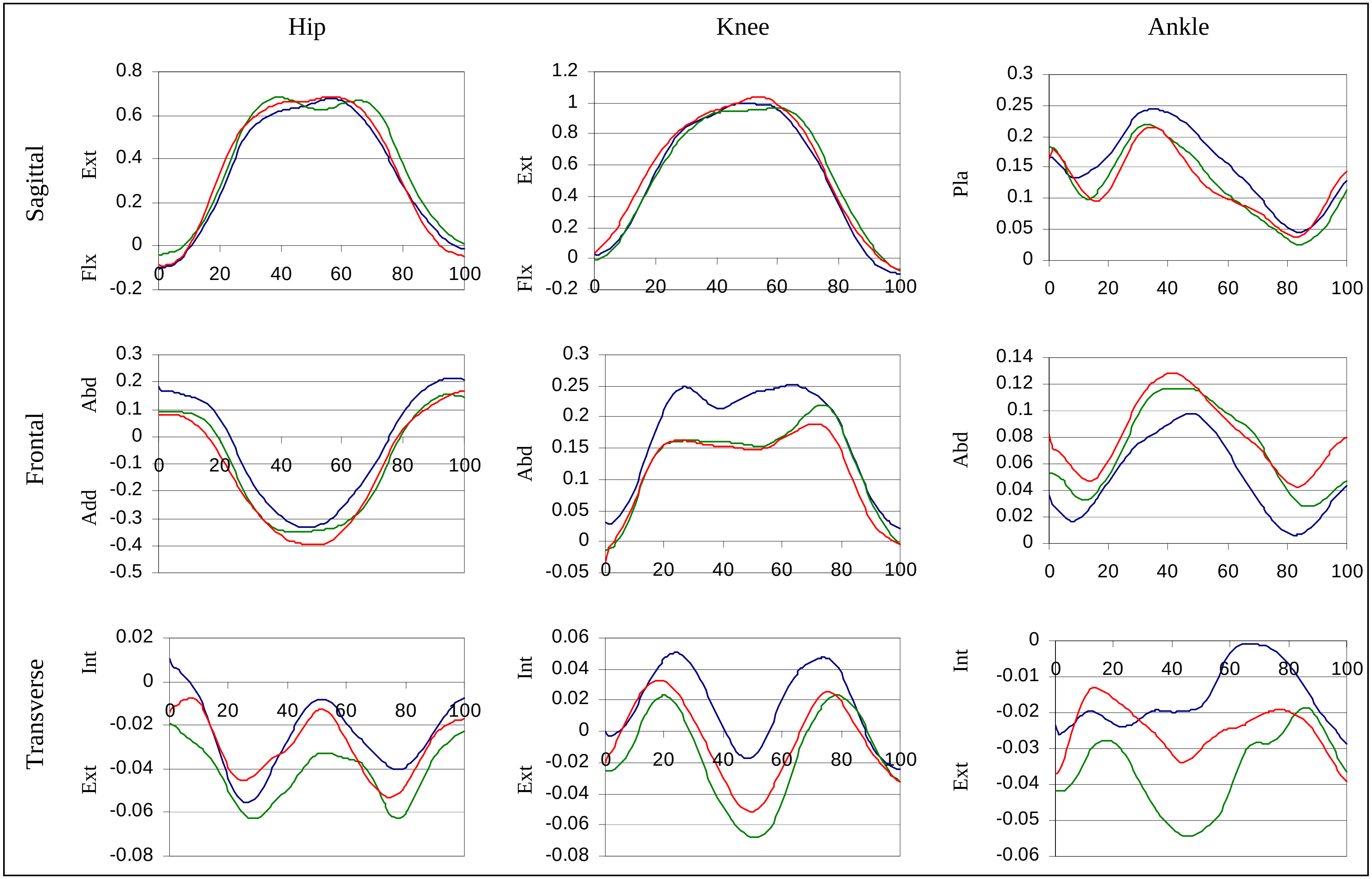

Figure D-9. Joint moments (Nm/kg) over one cycle of squatting: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

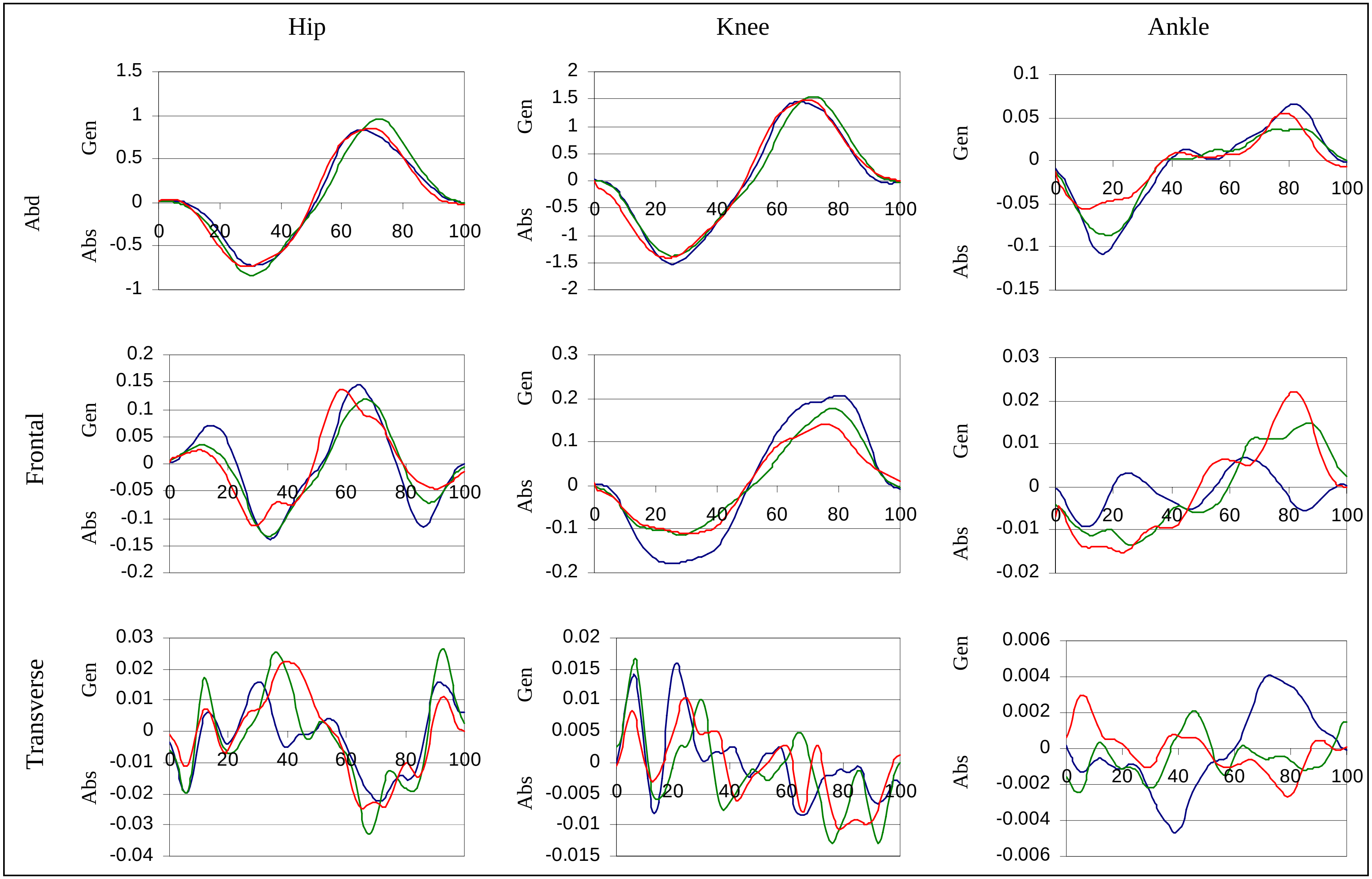

Figure D-10. Joint powers (W/kg) over one cycle of squatting: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

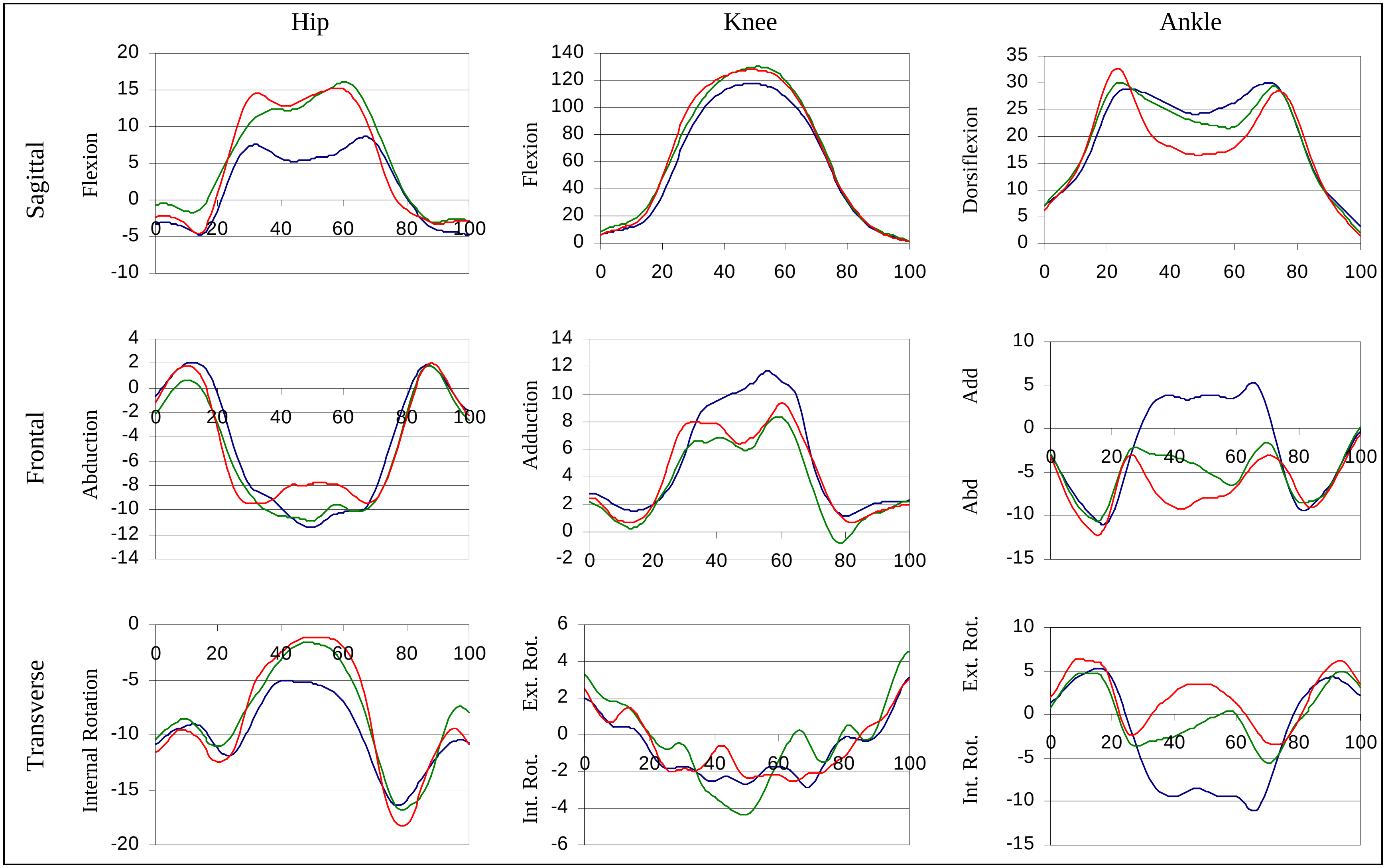

Figure D-11. Joint angles (degrees) over one cycle of right kneeling: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

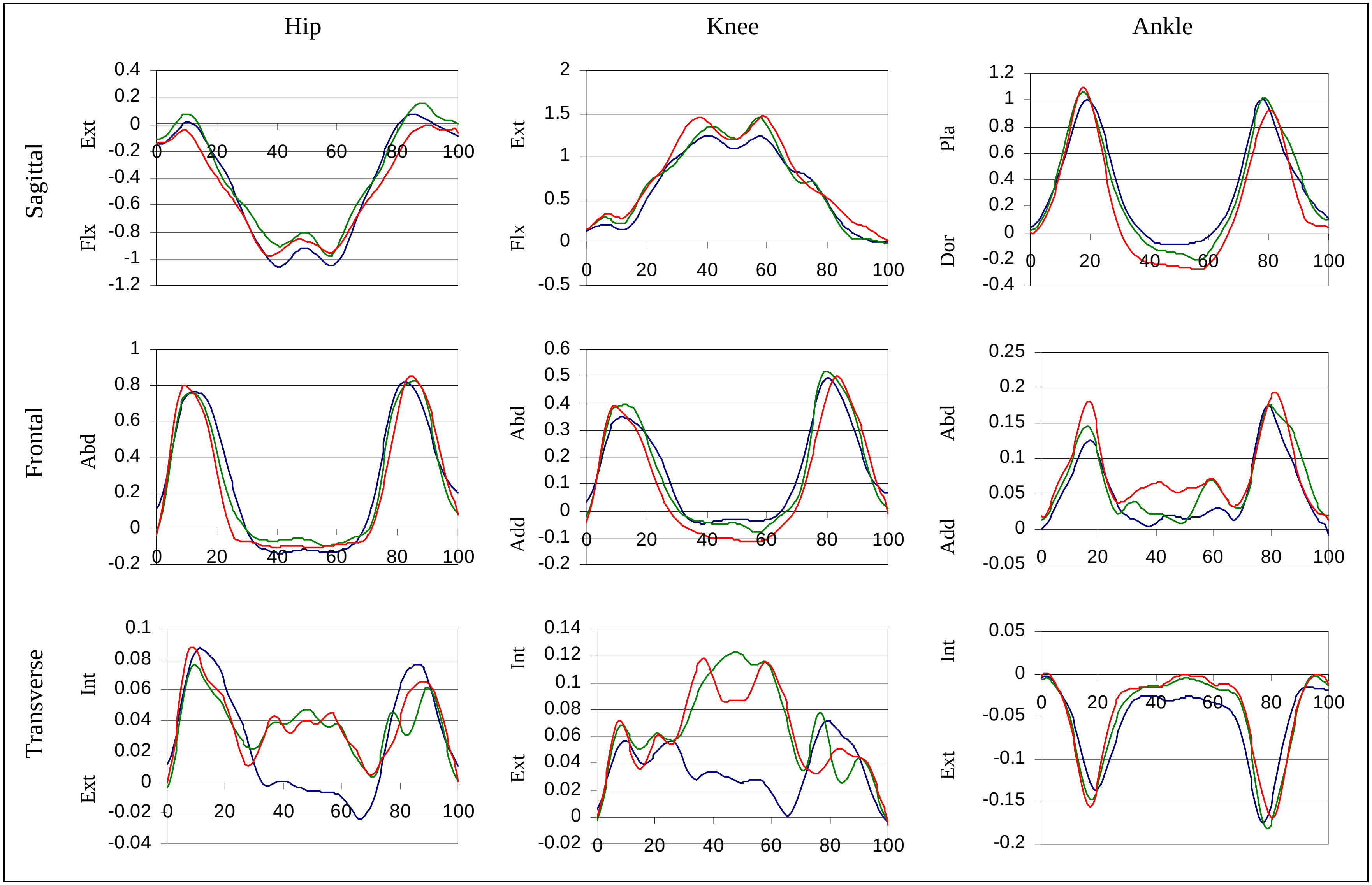

Figure D-12. Joint moments (Nm/kg) over one cycle of right kneeling: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

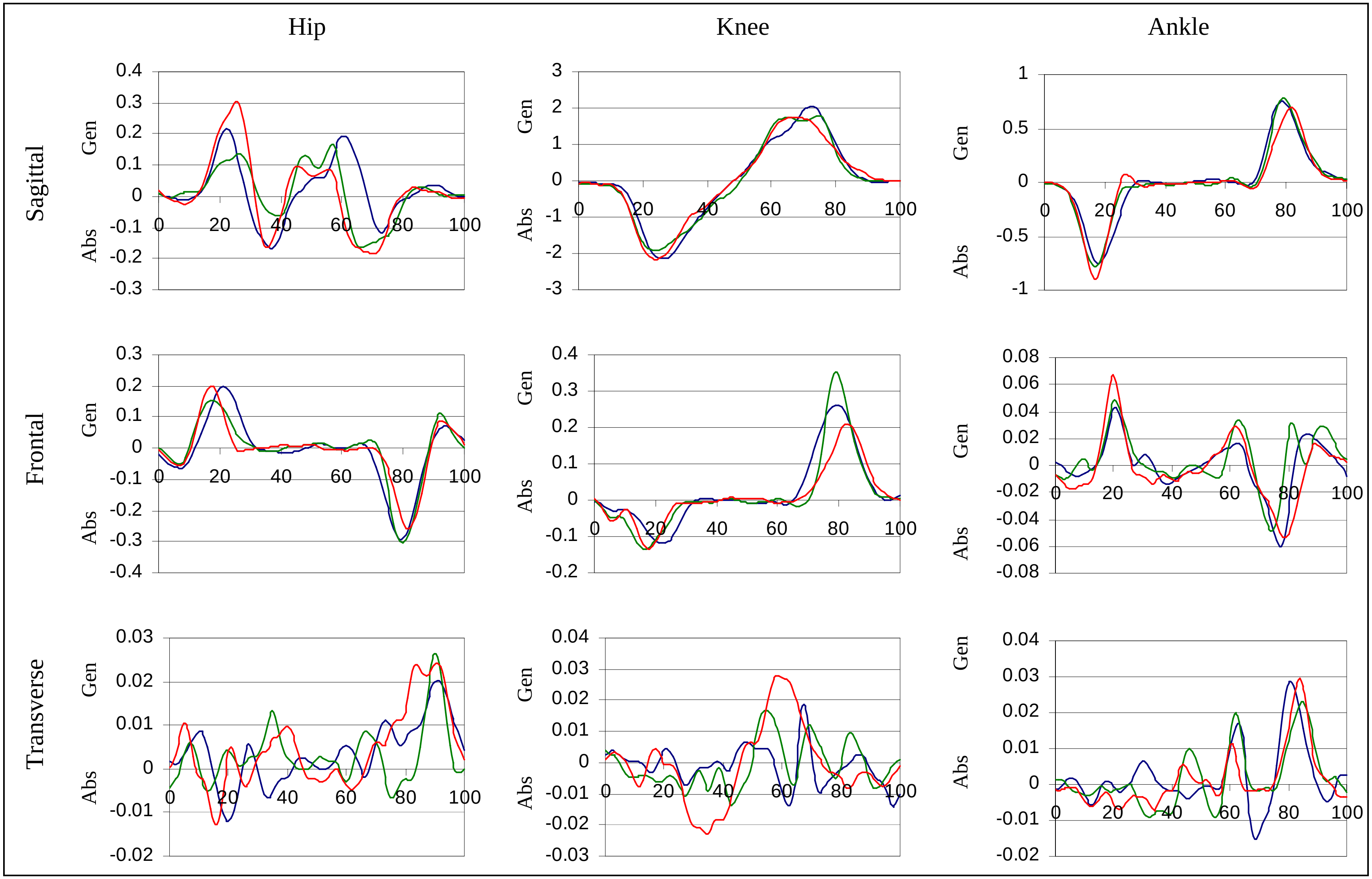

Figure D-13. Joint powers (W/kg) over one cycle of right kneeling: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

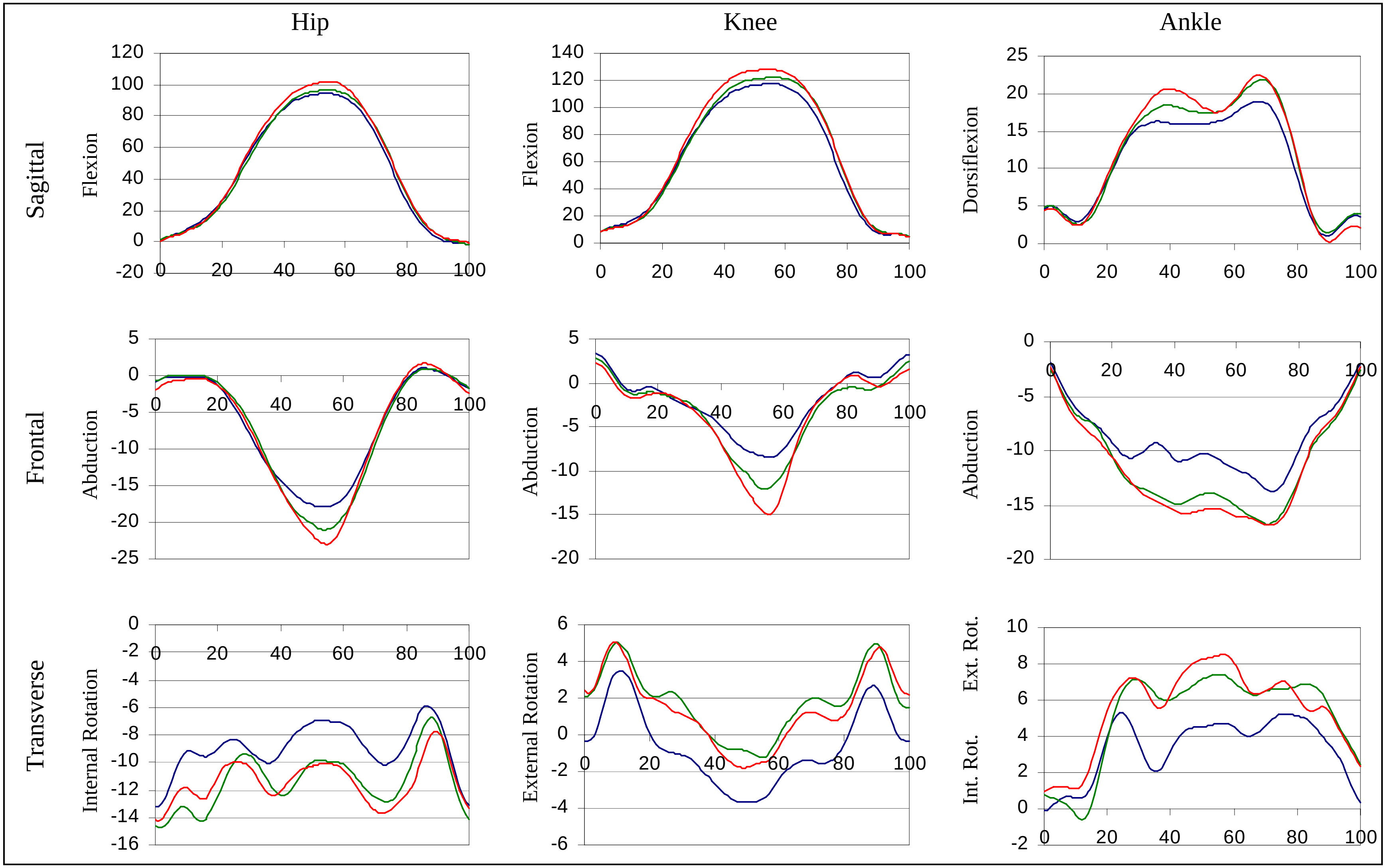

Figure D-14. Joint angles (degrees) over one cycle of left kneeling: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

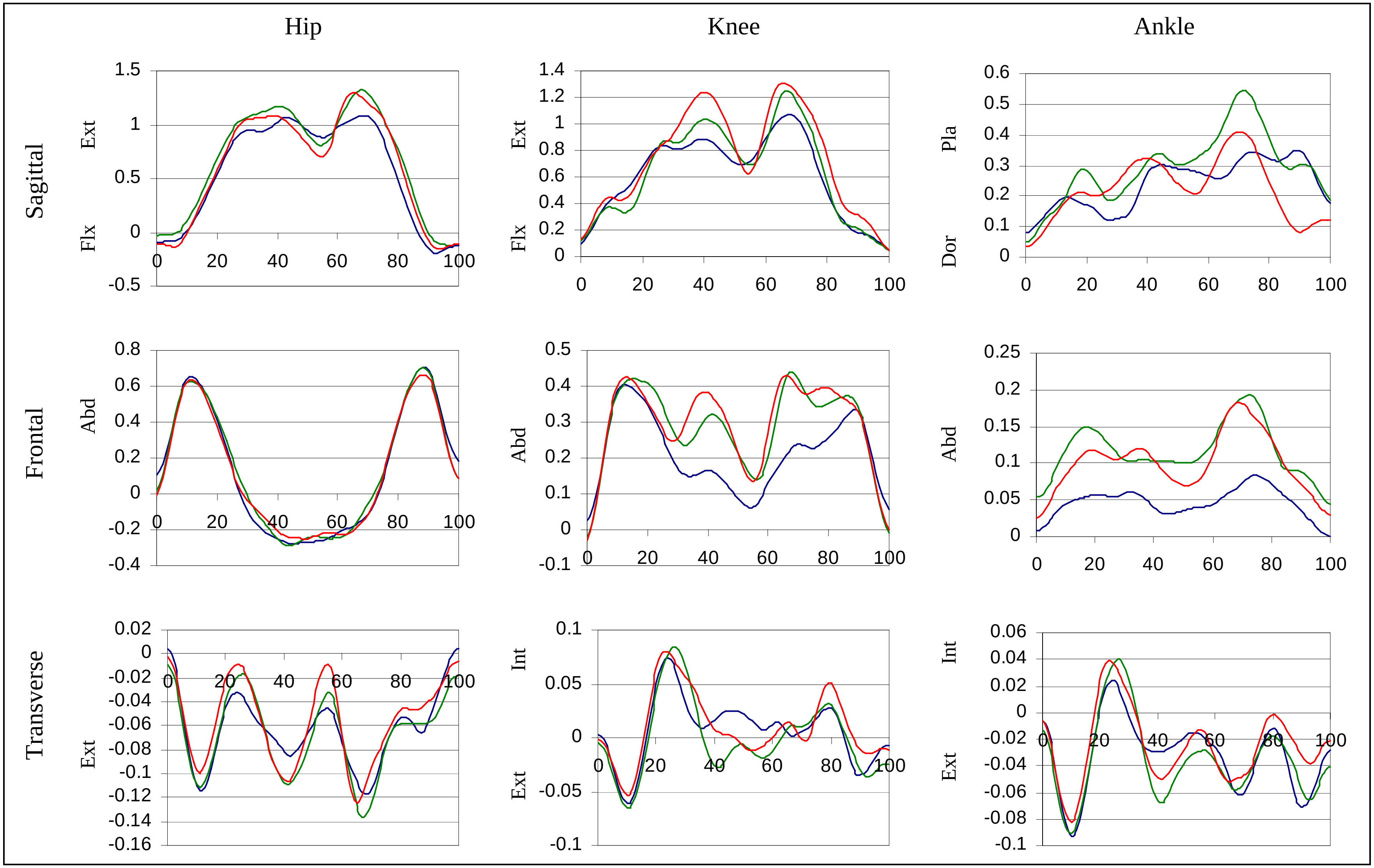

Figure D-15. Joint moments (Nm/kg) over one cycle of left kneeling: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

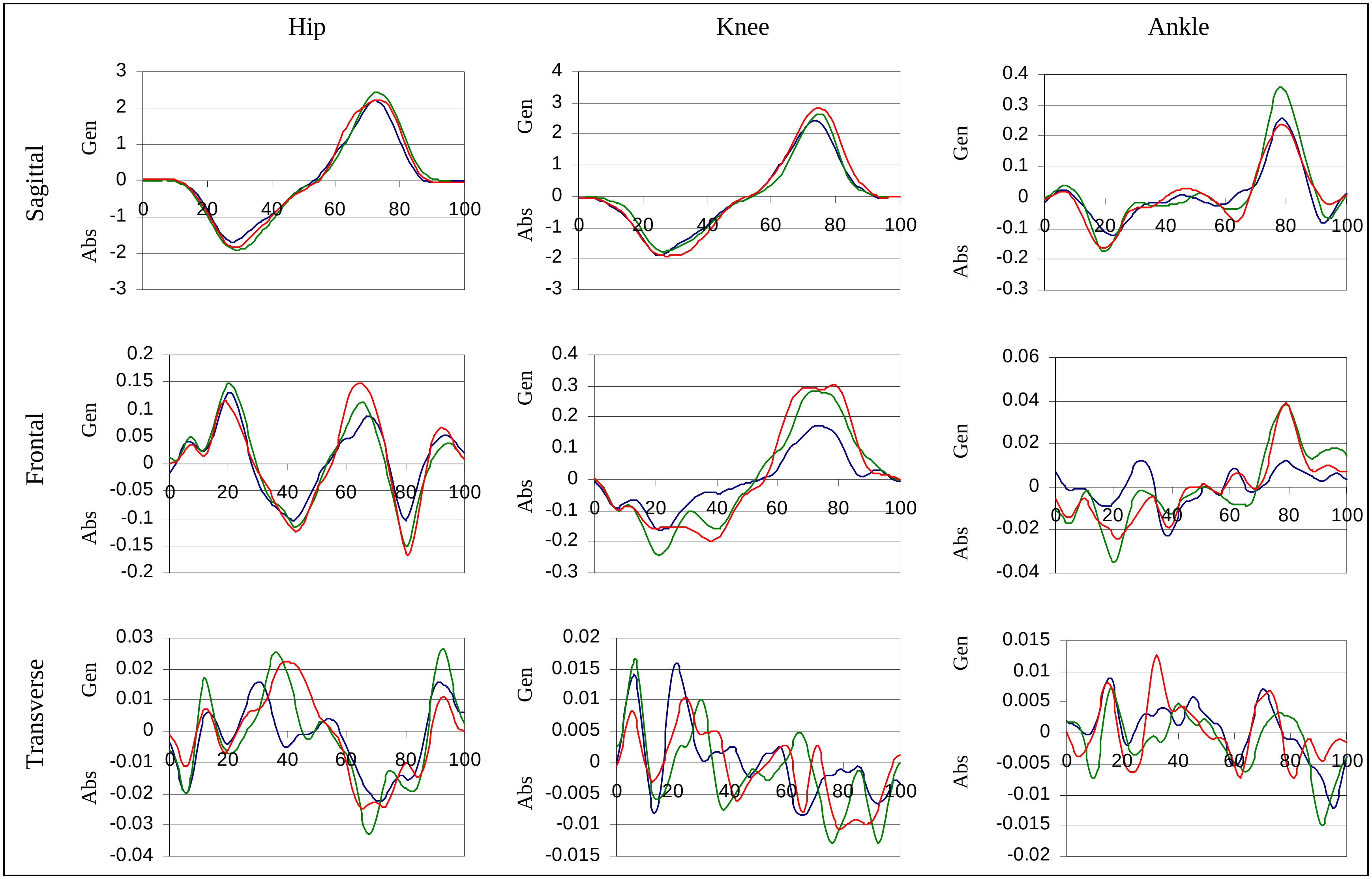

Figure D-16. Joint powers (W/kg) over one cycle of left kneeling: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

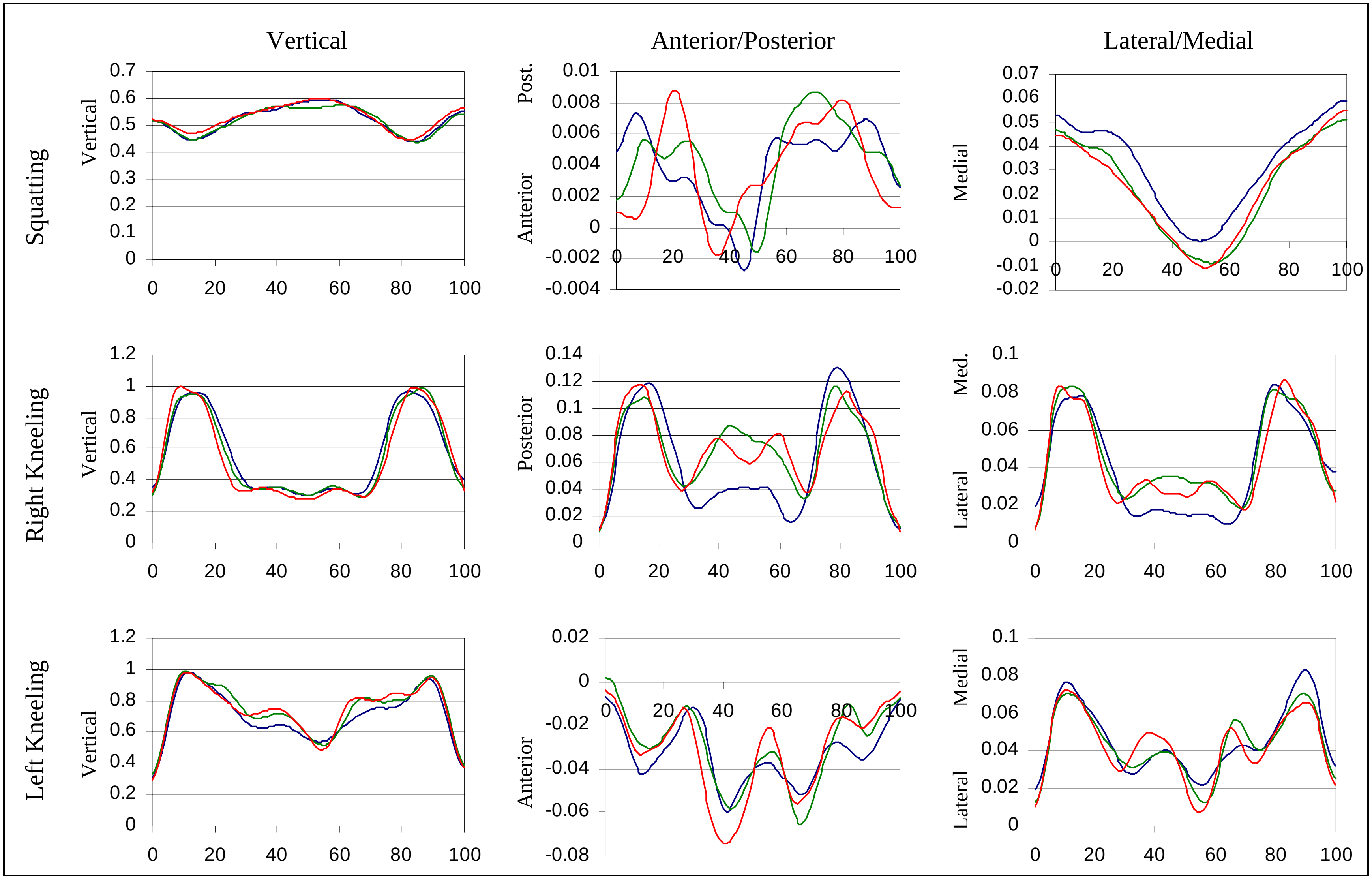

Figure D-17. Ground reaction forces (N/BW) over one cycle of squatting, right kneeling, and left kneeling: (Blue=Baseline, Green=1-inch Sole, Red=2-inch Sole), N=12.

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